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A three-dimensional quality-guided phase unwrapping method for MR Elastography

Huifang Wang^{a,*}, John B. Weaver^{a,b}, Irina I. Perreard^b, Marvin M. Doyley^c, and Keith D. Paulsen^a

^aThayer School of Engineering, Dartmouth College, Hanover, NH 03755 USA

^bDepartment of Radiology, Dartmouth-Hitchcock Medical Center, Lebanon, NH 03756 USA

^cDepartment of Electrical and Computer Engineering, University of Rochester, Rochester, NY 14627 USA

Abstract

Magnetic Resonance Elastography (MRE) uses accumulated phases that are acquired at multiple, uniformly spaced relative phase offsets, to estimate harmonic motion information. Heavily wrapped phase occurs when the motion is large and unwrapping procedures are necessary to estimate the displacements required by MRE. Two unwrapping methods were developed and compared in this paper. The first method is a sequentially applied approach. The three-dimensional MRE phase image block for each slice was processed by two-dimensional unwrapping followed by one-dimensional phase unwrapping approach along the phase offset direction. This unwrapping approach generally works well for low noise data. However, there are still cases that the two-dimensional unwrapping method fails when noise is high. In this case, the baseline of the corrupted regions within an unwrapped image will not be consistent. Instead of separating the two-dimensional and one-dimensional unwrapping in a sequential approach, an interleaved three-dimensional quality-guided unwrapping method was developed to combine both the two-dimensional phase image continuity and one-dimensional harmonic motion information. The quality of one-dimensional harmonic motion unwrapping was used to guide the three-dimensional unwrapping procedures and it resulted in stronger guidance than in the sequential method. In this work, *in vivo* results generated by the two methods were compared.

Keywords

Magnetic Resonance Elastography (MRE); phase unwrapping (PU)

1. INTRODUCTION

MR elastography (MRE) (Muthupillai et al., 1995, Muthupillai et al., 1996) and its predecessor, ultrasound elastography (Ophir et al., 1991), have been effective in differentiating pathology from normal tissues based on tissue stiffness. It has been employed productively in breast (Lorenzen et al., 2001, McKnight et al., 2002, Van Houten et al., 2003), brain (Ehman et al., 1997, Kruse et al., 2008, Green et al., 2008, Sack et al., 2008), liver (Rouviere et al., 2006, Yin et al., 2007), structural tissues (Weaver et al., 2002, Heers et al., 2003, Cheung et al., 2006) and more recently in the heart (Kolipaka et al., 2009). The stiffness of tissues determined using manual palpation is used in many clinical settings

*The author's current affiliation is: Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital/Harvard Medical School, 149 13th St., Charlestown, Massachusetts, 02129, USA

(Sarvazyan, 1993) and a more accurate, reproducible method holds a great deal of promise to improve clinical care.

MRE utilizes accumulated phases to estimate the motion which is used to reconstruct the mechanical properties of tissue. For dynamic MRE, continuous harmonic mechanical excitation is applied to the tissue. In order to detect the motion in the tissue, a motion sensitizing gradient is used to encode the motion information onto the phase of the MR raw data. Multiple phase images are acquired at evenly spaced relative phase offsets between the motion encoding gradient and the externally induced motion. The sampled phases of each pixel follow a harmonic wave and can be expressed as a function of the relative phase offset ϕ between the externally induced motion and the motion encoding gradients:

$$f(\phi) = A \cos(\phi + \theta), \quad (1)$$

where $\phi = 2\pi\phi_n/N$, ($\phi_n = 0, \dots, N-1$) and N is the number of evenly spaced phase offsets within one cycle. The amplitude, A , and phase, θ , characterize the harmonic motion completely and are estimated from the sampled $f(\phi)$ values (Sinkus et al., 2000).

When the accumulated phases, $f(\phi)$, are out of the $[-\pi, \pi)$ range, the true phase values will be wrapped back to this range, creating discontinuities in the phase maps and subsequently in the estimated motion. Thus the phase needs to be unwrapped before the motion can be estimated accurately. For each slice of tissue imaged, N different phase images are acquired at evenly spaced relative phase offsets along the time domain forming a three-dimensional phase image block. The dimension along the relative phase offset always follows one cycle of a harmonic wave function and the other two-dimensional phase images are usually continuous. The restrictions from the time dimension and the two spatial dimensions are totally different. Based on these characteristics, possible approaches are put forward to unwrap the MRE phase image block.

In order to unwrap the three-dimensional image block, a one-dimensional phase unwrapping method can be used to unwrap the harmonic wave along the relative phase offset dimension for each voxel. Fig. 1 shows the workflow for unwrapping the three-dimensional image block with one-dimensional phase unwrapping method only. Each voxel is unwrapped separately with the one-dimensional unwrapping method. One of the most commonly used one-dimensional phase unwrapping method is Itoh's method (Itoh, 1982). The method assumes that the adjacent phase differences are in the range $[-\pi, \pi)$, so that it can recover the wrapped large phase difference to the original $[-\pi, \pi)$ range. The method starts the unwrapping procedure from the first phase value and set it as true value. Then it wraps the adjacent phase difference into range $[-\pi, \pi)$ and accumulates this estimated phase difference onto the true value to get the next unwrapped phase. By following this similar step, each phase value can be unwrapped respectively. However, this method fails when the original adjacent phase difference is out of the range $[-\pi, \pi)$.

Another approach to unwrap the three-dimensional phase images is to apply a two-dimensional phase unwrapping method on each phase image. The baseline of each phase image is unwrapped afterwards with a one-dimensional unwrapping method to recover the harmonic wave along the phase offset dimension. Fig. 2 shows the detailed unwrapping procedures. This approach adds more constraints into the unwrapping procedure and is more stable. There are various two-dimensional unwrapping methods that could be applied to MRE phase images (Ghiglia and Romero, 1994). Currently used two-dimensional methods include: path-following integration methods, such as Goldstein's method, the mask cut algorithm, the quality-guided algorithm or Flynn's minimum discontinuity algorithm and minimum-norm methods, such as unweighted least-squares methods including

preconditioned conjugate gradient (PCG) method. Each of these methods was studied and the unwrapping results with MRE data are compared afterwards. The performance is evaluated based on the unwrapping results and execution time.

The Goldstein's method is a classic path-following phase unwrapping method which was developed by Goldstein, Zebker and Werner (Goldstein et al., 1988). The method searches for residues in the phase image and places branch cuts between nearby residues. In this way it removes the integration path dependency when unwrapping the phase image. The phase difference integration starts from the top left corner of the image and unwraps the phases with the assumption that adjacent pixels have phase differences within the range $[-\pi, \pi)$. Also the unwrapping path needs to integrate around branch cuts in order to remove the path dependency. However, when the branch cuts are placed in the wrong location, the unwrapping result can be incorrect.

The central idea of the quality-guided path following method is to unwrap along a path starting with the highest quality pixel where little unwrapping is required to the most ambiguous areas where the phases of adjacent better quality pixels can be used to inform the unwrapping. The quality map can be a correlation map, phase derivative variance map etc. When a correlation map is not available, the phase derivative variance map is generally used. In this map, the slowly varying phases are usually defined as high-quality regions and are unwrapped first. Then the rapidly varying phases are defined as low-quality regions and are unwrapped using the unwrapped phases from the higher quality regions as priors.

The minimum-norm methods are generally iterative and usually need more computation time than the path-following integration methods. Flynn's method (Flynn, 1997) tries to minimize the discontinuity of the phase image. The algorithm finds the path that can form the loop of discontinuity and removes the discontinuity by adding or removing 2π on the phase values within the loop region. The process is performed iteratively until no more discontinuity loops are found. A quality map can also be applied to guide the discontinuity placement. The PCG method (Ghiglia and Romero, 1994) treats unwrapping as a weighted least-squares problem. It unwraps the phase image by solving the partial differential equation iteratively. Conjugate gradient can be used to improve convergence. The weights are used to select high-quality nodes and mask out the corrupt region of the phase map. The comparison for using different two-dimensional unwrapping methods on MRE phase image block will be illustrated in more detail.

However, the two-dimensional unwrapping methods could introduce discontinuous regions when the noise is high. The resulting inconsistent baselines within a slice would produce an incorrectly unwrapped baseline. Then the one-dimensional baseline unwrapping could give incorrect results.

Three-dimensional phase unwrapping algorithms have been widely used in different areas, such as optical interferometry, synthetic aperture radar (SAR) and magnetic resonance imaging (MRI). Many of the methods apply quality map to guide the unwrapping procedures. A generalized minimum spanning tree approach was used in three-dimensional unwrapping under the guidance of quality map (Arevalillo-Herraez et al., 2010). Another approach defines the quality map with the quality of the edges that connect two neighboring voxels and unwraps the most reliable voxels first (Abdul-Rahman et al., 2007). Nevertheless most of these methods can not directly be used to MRE three dimensional image blocks. This is because one of the three dimensions is in temporal domain and follows one cycle of a harmonic wave function, while the other two dimensions are in spatial domain. The restrictions in two different domains are quite different. This situation leads us to introduce

an interleaved three-dimensional phase unwrapping approach, which considers the temporal domain and the spatial domain restrictions simultaneously.

2. METHODS

The three-dimensional quality-guided path following approach considers the two-dimensional constraints among the adjacent pixels and the motion fitting constraints simultaneously. The method applies the idea of quality-guided unwrapping to the three-dimensional image block. Each time it unwraps a $1 \times 1 \times N$ (N is the number of phase offsets) voxel along the phase offset dimension and the adjacent voxels. The quality map is determined by the motion fitting error along the third dimension -- phase offset dimension. The algorithm follows an iterative procedure and the quality map is updated continuously. In order to ensure that every high-quality voxel is unwrapped first, only the first N voxels with the least motion fitting error are checked and unwrapped in the N^{th} iteration. The method iterates until the last voxel is unwrapped. Fig. 3 demonstrates an outline of the unwrapping procedures.

The “standard” unwrapping algorithm has the following stages:

1. A one-dimensional pre-unwrapping is applied along the phase offset dimension using Itoh's method. The motion information is then estimated from the unwrapped phases. The absolute root-mean-square (RMS) fitting error between the unwrapped phases and the fitted motion samples is used as the initial quality map.
2. The voxel that has the least fitting error, named $C(x, y, :)$, is chosen to be a starting point of the unwrapping path. The unwrapped result by Itoh's method is used as a reference for the adjacent voxels $C(x+1, y, :)$, $C(x-1, y, :)$, $C(x, y+1, :)$ and $C(x, y-1, :)$. To unwrap the adjacent voxels, the difference between the reference pixel $C(x, y, i)$ ($i=1, \dots, N$) and the adjacent pixel, e.g. $C(x+1, y, i)$ ($i=1, \dots, N$), is forced to be within the range $[-\pi, \pi)$, given the assumption that the phase changes in the two-dimensional phase image do not change dramatically from pixel to pixel. The unwrapped voxels are then marked with a flag.
3. The quality map is then updated for all the voxels. In the next iteration, the voxel that has the second least fitting error is chosen to be the next unwrapping point. If the voxel is marked as unwrapped, the adjacent voxels can use the unwrapped value as the reference. If the voxel is not marked as unwrapped, the pre-unwrapping result is used as the reference. As the quality map is updated in this iteration, the voxel that has the best quality might be changed. If the best voxel has been changed and was not used as a reference before, it has to be unwrapped in this iteration and is then used as a reference for the adjacent voxels.
4. The quality map is updated at the beginning of each iteration. In the N^{th} iteration, the $1 \sim N^{\text{th}}$ best voxels are first checked or unwrapped. Then the ones that are not referenced before will be used as the reference for the adjacent voxels.
5. The iteration ends when the last voxel is unwrapped. The unwrapped phases and the motion estimation results are both finished in the last iteration.

There are several differences between the new unwrapping method and the sequentially applied two-dimension/one-dimension method. The new method can be described as an interleaved three-dimensional unwrapping method. It introduces a third dimension restriction voxel-by-voxel. Along the time dimension, voxels are forced to follow a harmonic wave and the adjacent time points could have phase difference out of the range $[-\pi, \pi)$. Meanwhile the spatial dimensions usually have phase difference within the range $[-\pi, \pi)$. Thus the different unwrapping procedures could not be applied simultaneously in

the usual way. However, when applying the phase difference method within each of the two spatial dimensions, the reference voxel already follows the time dimension restriction. It intrinsically integrated the two-dimensional spatial unwrapping with one-dimensional voxel unwrapping. In this sense, the two-dimensional and one-dimensional unwrappings of the new method are inter-connected. While for the sequentially applied two-dimension/one-dimension method, it totally separates the two-dimensional and one-dimensional unwrapping procedure. After the individual two-dimensional unwrapping for each image, a one-dimensional unwrapping is applied only on the baseline of the images.

The new method is an iterative method and it updates the quality map at the beginning of each iteration. All of the 1~Nth best voxels are to be evaluated at the Nth iteration in case any change occurs on the order of the voxels after each update. The sequential method is not an iterative method and the execution time is relatively shorter than the new method. In order to save execution time of the new method, a flag is added for each voxel to ensure it is not unwrapped twice. Another flag on the reference voxel can also help on saving execution time. A voxel can only be used as a reference once to prevent repeated unwrapping procedures.

The quality map of the new three-dimensional phase unwrapping method is obtained from the whole image block. It is the absolute root-mean-square (RMS) fitting error between the unwrapped phases and the fitted motion samples, which integrates harmonic information into the unwrapping. In the sequential method, the quality map is only based on the phase derivative variance between the adjacent pixels in two-dimensional images. It does not apply any harmonic information into the unwrapping nor have strong restrictions on MRE data.

The three-dimensional phase data space is filled in the order of quality ranking, which measures how good the phase offsets fit the harmonic wave. The path does not necessarily form a connected region and the next voxel could jump to another disconnected region if the voxel in that region has higher quality. In this way, it prevents the noise from spreading out to the high quality regions.

3. RESULTS

Two studies are presented in this section. The first study compares four different two-dimensional unwrapping methods, when unwrapping the three-dimensional MR phase image block with the sequential unwrapping procedures of two-dimensional unwrapping followed by a one-dimensional baseline unwrapping. One set of phantom data and one set of breast data were used for this study. The second study compares the new three-dimensional phase unwrapping method with the sequential unwrapping procedures. The study includes the phase unwrapping results from one set of agar phantom data and two sets of *in vivo* data: one of a cat brain and the other of a breast. The phase images in the breast data usually have continuous waveform with large motion amplitude, which are quite different from those in the cat brain where the motion is small and the phase images are discontinuous in some regions.

A spin echo pulse sequence with motion sensitizing gradients was used to collect all the data on a 3T Philips Achieva MRI system. The vibration frequency of the objects is 100 Hz. Eight phase images were taken at different phase offsets and the motion along this dimension follows a harmonic wave function.

Study I

A high signal and low noise phantom data set with several regions where the phase is wrapped was used to test these methods. The original raw phase images for one slice

acquired with eight phase offsets are shown in Fig. 4(a). Discontinuous regions were found in each image. Different unwrapping methods were then applied and Fig. 4(b) shows the resulting phase images. All the methods were found to unwrap the images successfully and the results were identical. The motion amplitude map estimated from the unwrapped phase images and the estimation error are shown in Fig. 5. The average estimation error is 1.79%. Thus when the original data is clean and not too noisy, all of the methods are found to unwrap the images correctly.

Although all of the methods work well for high SNR data, the different two-dimensional unwrapping methods produce different results for noisy MRE data. A clinical breast data set was unwrapped with the four methods. Eight phase offsets were acquired and all the phase images were wrapped. The phases for one of the slices are shown in Fig. 6(a). The images are generally noisier than the phantom images with almost vanishing signal in some regions. Fig. 6(b) is the unwrapped result from the quality-guided path following method. The unwrapping results from the four methods are different and the performance was evaluated with the estimated motion map and the estimation error, which are shown in Fig. 7. The estimation error is the absolute root-mean-square (RMS) fitting difference calculated between the unwrapped phases and the fitted motion samples along the phase offset dimension. The motion maps are on the top and the estimation error maps are on the bottom. The four columns correspond to the results from Goldstein, quality-guided, Flynn and PCG methods. Some large regions that have relatively high estimation error are observed from using the Goldstein and Flynn methods. The motion maps also show discontinuities in the corresponding regions. The quality-guided and PCG methods both give smoother motion and error maps, while the PCG method produces higher error than the quality-guided method. Even the error map from the PCG method looks smoother than quality-guided method in some areas, the overall error map is darker. This is because the PCG method essentially smoothes the noisy region and produces large changes over those regions. The method uses least-squares formulation to minimize the squares of the gradient differences. The unwrapped result is actually an output surface that fits the minimum gradient solution. When the surface is re-wrapped, the resulting phase is not necessarily the same as the wrapped input phase. In this sense the PCG method is less optimal for MRE data since the accurate phase values are required to estimate the motion. Instead the quality-guided method provided superior unwrapping results for the data that is contaminated by noise.

The execution times of all four methods for two different datasets are listed in Table 1. They are the averaged execution time for 10 trials.

The ranking of execution time from all methods differs a little for phantom and *in vivo* data. The quality-guided method costs less time for phantom data, while for *in vivo* data the Goldstein method requires less time. In both cases, the PCG method is the slowest. The Flynn method is also quite slow compared with the Goldstein and the quality-guided methods. Thus the quality-guided method produces better unwrapped images with relatively short computation time. This two-dimensional method can be selected for the sequential approach and it generally works well for phantom and low noise *in vivo* data.

However, the sequential unwrapping procedures of two-dimensional unwrapping followed by a one-dimensional baseline unwrapping does not always give correct results when the noise is high. The unsuccessful two-dimensional unwrapping can introduce discontinuous regions, which result in inconsistent baselines within a single phase image. When estimating the motion for each pixel, large errors will be generated from the inconsistent baselines. The following study is presented to compare the sequential unwrapping procedures with the three-dimensional phase unwrapping approach, which considers the two-dimensional restrictions between adjacent pixels and the motion fitting factors simultaneously.

Study II

a. Phantom test—A set of phantom data was acquired to test the unwrapping results from different unwrapping approaches. A three-dimensional phase image block is acquired for one slice of the gel at evenly spaced phase offsets. Phase images were taken at eight different phase offsets between the motion and motion encoding gradients. The eight images were first unwrapped with the two-dimensional quality-guided phase unwrapping method. The averaged baseline was calculated for each image after masking out the region of air that surrounds the phantom. Then the one-dimensional Itoh's method was used to unwrap the baselines and complete unwrapping the whole image block. The amplitude and phase information were estimated from the unwrapped phase images using an FFT (Sinkus et al., 2000, Wang et al., 2006). The whole image block was also unwrapped with the new three-dimensional quality-guided phase unwrapping method. In order to show the difference between these two unwrapping approaches under different noise levels, the normally distributed white noise with variable amplitude was added to the raw phantom data. The unwrapping results were then compared at different noise levels to differentiate the effectiveness of different unwrapping approaches. Fig. 8 shows the estimated amplitude map and the absolute fitting error map from the unwrapped raw phase for each different SNR level. Part (a) shows the amplitude map and part (b) shows the error map. In each part, the left image is estimated from the raw phases via the sequential unwrapping and the right image is via the three-dimensional quality-guided method. When SNR equals three or two, which means 33.3% or 50% random noise is added to the raw MR data, the results from both methods are similar in the phantom data. The estimation error is large in the air when using the sequential unwrapping approach. As the SNR was decreased to one, the estimation results in the phantom data diverge. The result from the sequential approach is found to have larger unwrapping error over a larger area than the three-dimensional quality-guided method. Smaller regions of large unwrapping error are present in the results from the new quality guided method. However, the high error regions didn't propagate into adjacent regions.

b. *in vivo* test – breast data—A data set was acquired on a subject using the same protocol as applied to the phantom data. The same image processing procedures were accomplished on the breast data. The estimated motion amplitude from using the sequential phase unwrapping procedures is shown on the left of Fig. 9(a) and the relative estimation error is shown on the left of Fig. 9(b). Several areas in the error map show large relative errors that are above one. They are caused by the unsuccessful unwrapping on the two-dimensional images using the two-dimensional quality-guided method. Fig. 10 shows the unwrapped results. Some phase images do not have consistent baselines. When the averaged baselines are unwrapped using Itoh's method, the inconsistency would bring in large errors and affect the following motion estimation.

The whole image block was then unwrapped using the new three-dimensional quality-guided phase unwrapping method. The estimated amplitude and the relative error are shown on the right of Fig. 9(a) and Fig. 9(b). The estimation error decreased substantially using the new method. Even though some noisy regions exist near the boundary of the breast, most of the regions still show reasonable results.

c. *in vivo* test – cat brain data—Another *in vivo* study was obtained using a cat brain. The phase images in the cat brain study provided examples of discontinuous regions, which are unusual in the breast data. Fig. 11(a) shows eight wrapped phase images acquired at different phase offsets on one slice of the cat brain. Two regions that are inferior to the brain are found to be $-\pi$. It might be due to the low signal-to-noise ratio in these regions and the phase is indeterminate when the signal is zero. When the two-dimensional quality-guided

phase unwrapping method is applied on these phase images, the method could unwrap the $-\pi$ value into $-\pi + 2n\pi$ (n is integer) values. This could be found in the unwrapped phase images shown in Fig. 11(b). The values in the two regions on all the unwrapped images do not retain the $-\pi$ value. The estimated motion amplitudes from the unwrapped images are not zero, but an incorrect value. The error map in Fig. 12 (right) shows large relative error for the amplitude estimation in these regions.

When the new method is applied to the three-dimensional cat data set, the estimated motion amplitude and the estimation error map from the unwrapped phase images are shown in Fig. 13. The estimated amplitude map shows the two regions which are inferior to the brain with almost zero motion, while these regions could not be identified via the sequential unwrapping approach. Several other smaller regions of very low motion were also identified by using the new method. In this sense, the new method did have the ability to distinguish the discontinuous regions that have different levels of motion.

During the unwrapping process, the mask was not used for this dataset. But the reconstructed amplitude map didn't show the errors along the boundary of the cat brain as the sequential unwrapping method did. By following the quality map, the method did prevent the noise from spreading out and isolated the low quality regions.

By comparing the two *in vivo* datasets, the breast data appears to be more demanding for phase unwrapping. Different from the cat brain, the motion waveform in the breast is often continuous and the motion amplitude is usually observed to be larger compared to that in the cat brain. In addition, even the cavities with almost zero motion exist in the cat brain, they could be masked out based on an anatomical image. The cat brain data is used to provide the example of discontinuous regions, which are unusual in the breast data.

d. Comparison of execution time—The same phantom and *in vivo* data used in Table 1 were unwrapped with the sequential unwrapping method and the three-dimensional quality-guided method. The execution times of two methods on two different datasets are listed in Table 2. They are the averaged execution time for 10 trials.

The three-dimensional quality-guided unwrapping method generally takes longer time than the sequential unwrapping method. However the iterative procedures of the new method give acceptable execution time.

e. The unwrapping results with different quality maps—Different quality maps may lead to different unwrapping results when the three-dimensional quality-guided unwrapping method is applied. In this section, several different quality maps were applied during the unwrapping process and the unwrapping results were compared.

Another three-dimensional phase image block was acquired for one slice of breast at evenly spaced phase offsets. The three-dimensional quality-guided unwrapping method was applied on the image block. The first quality map applied was the absolute root-mean-square (RMS) fitting error between the unwrapped phases and the fitted motion samples along the phase offset dimension. The reconstructed motion amplitude and the estimation error map from the unwrapped image block are shown in Fig. 14. The second quality map applied was the relative RMS fitting error relative to the estimated amplitude. The reconstructed motion amplitude and the estimation error map are shown in Fig. 15. It is found that when using relative error as the quality map, the estimated motion map has more error on the boundary of the breast. These regions have relatively small amplitude and large noise. Based on the second quality map, the voxels in these regions could form a large amplitude motion wave

with relatively small noise and cause wrong unwrapping result. Thus the quality map based on relative error is more sensitive to the noise than the one with absolute error.

The third quality map was selected as the absolute RMS fitting error integrated with the magnitude of the raw MR image. Both the magnitude of the MR signal and the fitting error contribute to the quality of the pixel. Fig. 16 shows the unwrapped result using this third quality map. The reconstructed amplitude and the error maps only show small differences between results when the third and the first quality maps are used. This is because the large magnitude of the MR signal usually corresponds to the high quality of the voxel.

4. CONCLUSION

A new three-dimensional quality-guided phase unwrapping method was developed by extending the two-dimensional quality-guided phase unwrapping method. The algorithm employs both constraints of two-dimensional image phase continuity and the sinusoidal shape along the phase dynamic dimension. Therefore, the new method is more robust than the sequential unwrapping procedures. The new method successfully deals with noisy MRE phase data, especially *in vivo* data, on which the sequential quality-guided unwrapping fails. By analyzing different *in vivo* data sets, the new approach showed the ability to unwrap the high quality regions correctly and prevent the low quality regions from contaminating adjacent regions.

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Figure 1.
Workflow of one-dimensional phase unwrapping on MRE image block.

Figure 2.
Workflow of two-dimensional phase unwrapping on MRE image block.

Figure 3.
The three-dimensional quality-guided path following unwrapping method.

Figure 4.
(a) The phantom raw phase image series for one slice acquired with eight phase offsets. (b) The unwrapped phase image series. Different methods produce the same unwrapping results.

Figure 5.
The motion amplitude map (left) and the estimation error (right) estimated from the unwrapped phase images.

Figure 6.
(a) The *in vivo* raw phase image series for one slice acquired with eight phase offsets. (b) The unwrapped phase images from the two-dimensional quality-guided unwrapping method.

Figure 7.
The motion amplitude and the error maps estimated from the unwrapped phase images via Goldstein, quality-guided, Flynn and PCG methods (from left to right).

Figure 8.
The estimated amplitude (part a) and error (part b) maps from using two different unwrapping approaches, when three different levels of noise are added onto the phantom raw data.

Figure 9. The motion amplitude (in radian, part a) and relative estimation error (part b) maps estimated from the unwrapped results following the sequential unwrapping approach (left) and the three-dimensional quality-guided method (right).

Figure 10.
The unwrapped phase image series of the breast with two-dimensional quality-guided phase unwrapping method.

Figure 11. The wrapped (a) and unwrapped (b) phase images of the cat brain with two-dimensional quality-guided phase unwrapping method.

Figure 12. The motion amplitude map (left) and the estimation error map (right) estimated from the unwrapped phase images of the cat brain with the sequential two-dimension/one-dimension phase unwrapping method.

Figure 13.

The motion amplitude map (left) and the estimation error map (right) estimated from the unwrapped phase images of the cat brain with the new three-dimensional quality-guided phase unwrapping method.

Figure 14. The motion amplitude map (left) and the estimation error map (right) estimated from the unwrapped phase images of the breast using the absolute RMS fitting error.

Figure 15.
The motion amplitude map (left) and the estimation error map (right) estimated from the unwrapped phase images of the breast using the relative RMS fitting error.

Figure 16.

The motion amplitude map (left) and the estimation error map (right) estimated from the unwrapped phase images of the breast using the absolute RMS fitting error integrated with the magnitude of the raw MR image.

Table 1

Execution time comparison

	Phantom (s)	<i>In vivo</i> (s)
Goldstein	1.36 $\pm$ 0.05	1.22 $\pm$ 0.03
Quality-guided	1.33 $\pm$ 0.03	1.34 $\pm$ 0.02
Flynn	1.50 $\pm$ 0.08	1.44 $\pm$ 0.03
PCG	1.80 $\pm$ 0.03	1.76 $\pm$ 0.04

Table 2

Execution time comparison between 2D/1D sequential and 3D quality-guided unwrapping.

	Phantom (s)	<i>In vivo</i> (s)
2D/1D Sequential Quality-guided	1.33 $\pm$ 0.03	1.34 $\pm$ 0.02
3D Quality-guided	3.55 $\pm$ 0.03	2.12 $\pm$ 0.05