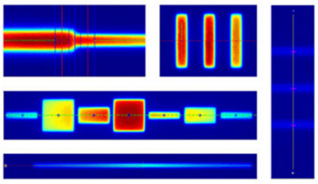
Medical Physics
The International Journal of Medical Physics Research and Practice

Correction of phase wrapping in magnetic resonance imaging

Leon Axel and Daniel Morton

Citation: Medical Physics **16**, 284 (1989); doi: 10.1118/1.596378
View online: http://dx.doi.org/10.1118/1.596378
View Table of Contents: http://scitation.aip.org/content/aapm/journal/medphys/16/2?ver=pdfcov
Published by the American Association of Physicists in Medicine

---



Correction of phase wrapping in magnetic resonance imaging

Leon Axel and Daniel Morton
Department of Radiology, Hospital of the University of Pennsylvania, Philadelphia, Pennsylvania 19104

(Received 3 January 1989; accepted for publication 17 January 1989)

In phase reconstruction MR imaging, e.g., for velocity measurement, phase shifts beyond $\pm\pi$ radians will "wrap around" to smaller apparent phases. Such large phase shifts could arise either due to large background (non-flow-related) phase variations or due to large velocity-induced phase shifts. For sufficiently smooth phase variation, such discontinuities can be automatically recognized and corrected, thus restoring the correct phase values and extending the effective dynamic range of such phase imaging techniques.

INTRODUCTION

In conventional magnetic resonance (MR) imaging, only the magnitude of the received signal is displayed in the final image. However, the phase is also of interest in many applications, such as in some techniques for the measurement of blood flow.[1-14] If the value of the phase extends beyond $\pm\pi$ radians, the redundant phase will be folded back into this range, leading to ambiguity in the final value. Such large phase shifts could result either from large variations in the background phase (unrelated to motion) or from large phase shifts due to the motion or other property being studied as a phase shift. In correcting for background phase variations, care must be taken in the region of such phase wrapping. This may still leave phase wrapping due to too large a range in phase, induced by the property being studied. In order to avoid this wrapping, we must reduce the dynamic range of the technique, thus reducing its sensitivity to the desired property. Alternatively, as the variation in phase will generally be relatively smooth, we would frequently expect to be able to use neighborhood information to detect discontinuities in phase due to wrapping and then to be able to patch across the discontinuity by adding or subtracting pi to restore a smooth phase across the region of the jump. We have implemented such a phase wrap correction technique for application to the phase measurement of flow.

MATERIALS AND METHODS

Baseline phase shifts, arising from such causes as miscentering of data acquisition windows, magnetic field gradient settling times, and RF penetration effects, should be compensated for prior to measurement of the phase shift due to a desired property such as velocity. For example, the schematic pulse sequence shown in Fig. 1 can be used to produce a velocity-sensitized phase image by acquiring signals which differ only in their degree of sensitization to motion-induced phase shifts. When subtraction is performed (either on the complex signals or on complex images reconstructed from them), the resulting phase image will have values proportional to the local velocity.

Where the background phase wraps around $\pm\pi$, straightforward subtraction of the images can result in values outside the range of representation. This is because even if two phase angles are similar, if they straddle the $\pm\pi$ transition, they can appear to have a large difference (on the order of $\pm 2\pi$). If truncated, these values will appear as artifacts in the region of the phase jump in the final subtracted image. These artifacts can be avoided by taking the phase difference modulo 2π.

Even after correcting for background phase variations, the desired phase shifts may be greater than $\pm\pi$. This can lead to wrapping and incorrect values in the final image. To avoid this, we can reduce the amount of phase shift produced by a given value of the desired property, e.g., velocity, so that the shift from the maximum expected value will fall within the range of $\pm\pi$. However, this will result in reduced sensitivity to small velocities. Alternatively, as long as the expected underlying phase variation with position is sufficiently smooth, we can look for discontinuities due to phase wrapping. We can then restore the appropriate $\pm\pi$ jump in phase to recover the correct velocity without having to reduce the velocity sensitivity. For practical application, this

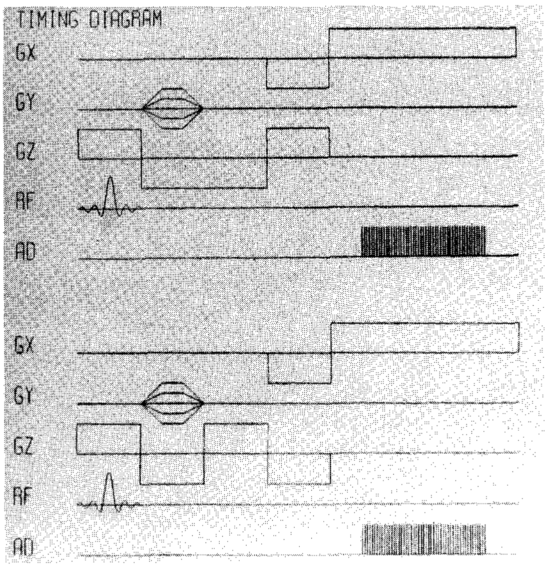


FIG. 1. Schematic imaging pulse sequence for imaging phase shifts corresponding to velocities at right angles to the slice selection plane (here "z"). Similar techniques can be used to sensitize to flow in any other desired direction. The final image displays the phase of the difference of the signals acquired with two pulse sequences which differ only in the degree of sensitization of phase to motion along the z direction, produced by differences in the compensating magnetic field gradient pulse pair in GZ. Here the upper pulse sequence is flow compensated, while the lower pulse sequence is flow sensitized.

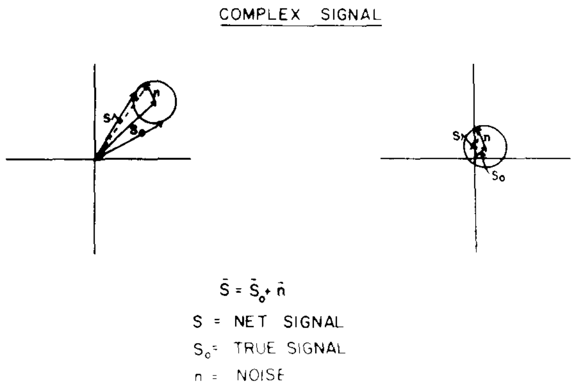


FIG. 2. Dependence of the phase of the net observed signal on the relative magnitudes of the true signal and random noise. For the case on the left, where the signal-to-noise ratio (SNR) is relatively large, the uncertainty in the phase due to noise is relatively small. However, for smaller SNR, as on the right, noise can introduce a large uncertainty into the phase of the net signal.

correction should be carried out automatically.

Our implementation uses neighborhood information to assign "true" phase values to pixels with smooth variation of phase. A region of interest containing vessels with wrapped phase is demarcated. Starting at one corner of the subimage, the initial pixel is assigned a true phase. Making multiple passes over the subimage, the phase of each pixel is assigned as correct if it is within a predetermined amount ($\pm \pi$) of the mean of all neighbors (we here use the eight nearest pixels) that have already been assigned a true phase, and it is so "marked." Discontinuities due to phase wrapping will produce isolated regions, with "unmarked" boundaries. At these discontinuities, in subsequent passes over the image, offsets of $\pm \pi$ are applied to produce the best fit smooth variation of phase. Multiple orders of wrap, producing nested discontinuities, can be handled in this way.

Magnitude information can be used to avoid regions where the phase is poorly determined due to low signal-to-

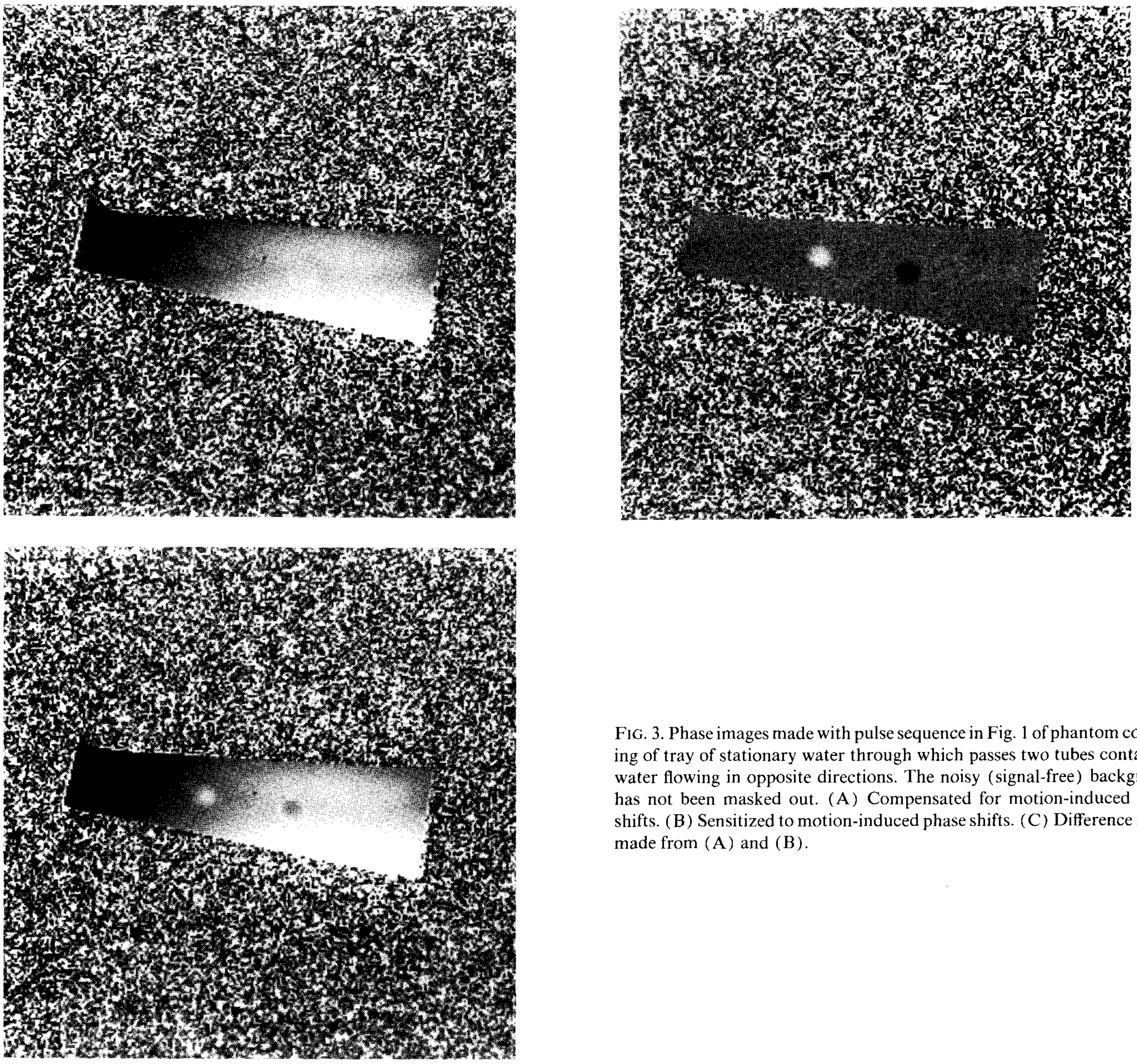


FIG. 3. Phase images made with pulse sequence in Fig. 1 of phantom consisting of tray of stationary water through which passes two tubes containing water flowing in opposite directions. The noisy (signal-free) background has not been masked out. (A) Compensated for motion-induced phase shifts. (B) Sensitized to motion-induced phase shifts. (C) Difference image made from (A) and (B).

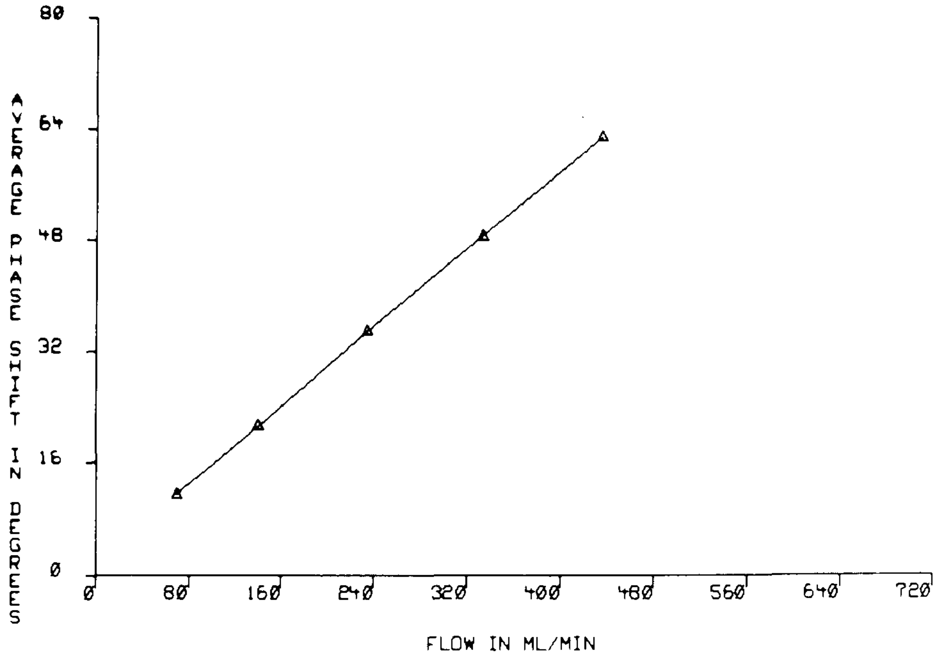


FIG. 4. Average phase obtained in baseline-corrected images of flowing fluid in Fig. 3 for different flow rates.

noise ratio (Fig. 2). If such masking out of pixels results in an isolated region, it can be handled in the same way the image as a whole was.

The principal constraint is the need for sufficient "smoothness" of the underlying phase variation. Specifically, there is an effective "sampling limit" such that the phase wrap within a given pixel must be less than pi in order to avoid ambiguity in the assignment of phase.

This phase wrap correction technique was implemented on a laboratory-built 1.9T MR imaging system. Flow phantoms filled with stationary water through which passed tubes carrying flowing water were imaged with the pulse sequence shown in Fig. 1. The pulse sequence repetition time, TR, was 35 ms; the echo time, TE, was 11 ms. The resulting phase images were corrected with the methods described above.

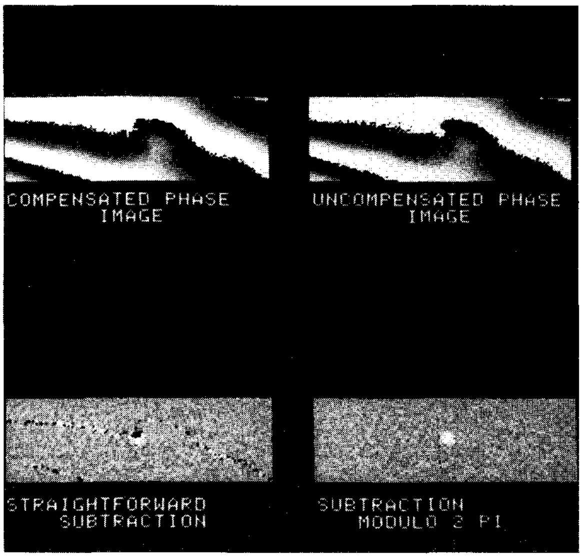


FIG. 5. Phase images of phantom consisting of single tube of flowing water passing through stationary water, with larger baseline phase variations than in Fig. 3. (A) Image acquired with top sequence of Fig. 1. (B) Image acquired with bottom sequence of Fig. 1. (C) Simple subtraction of (A) and (B), showing overall correction of background phase variation, but errors at the wrap boundaries. (D) Subtraction modulo 2π.

RESULTS

When the phase shifts do not exceed $\pm\pi$, the subtraction of images made with different degrees of phase sensitization can compensate for baseline phase shifts (Figs. 3 and 4). Even if the background phase shifts exceed $\pm\pi$, resulting in phase wrap, the subtracted image can correct for the baseline phase variation if care is taken to avoid truncation artifacts (Fig. 5).

When the phase shifts due to motion exceed $\pm\pi$, the technique described above can be used to correct for phase wrap and restore the true phase values (Fig. 6). Using the imaging system's own computer, the phase correction required approximately 5 s per subimage.

DISCUSSION

Wrapping of the background phase need not prevent correction for baseline phase variation, if care is taken to avoid truncation artifacts. Wrapping of the desired phase shifts due to values beyond $\pm\pi$ can also be retrieved, even with multiple orders of wrapping [as manifested by the concentric rings of discontinuity in the lower left image in Fig. 6(A)]. When the phase wrap exceeds π in a given pixel, we cannot unambiguously track across the discontinuity. For example, the concentric discontinuities touch in the lower right image in Fig. 6(A), leading to residual discontinuities in the corresponding image in Fig. 6(B).

Even though this technique cannot correct for arbitrarily

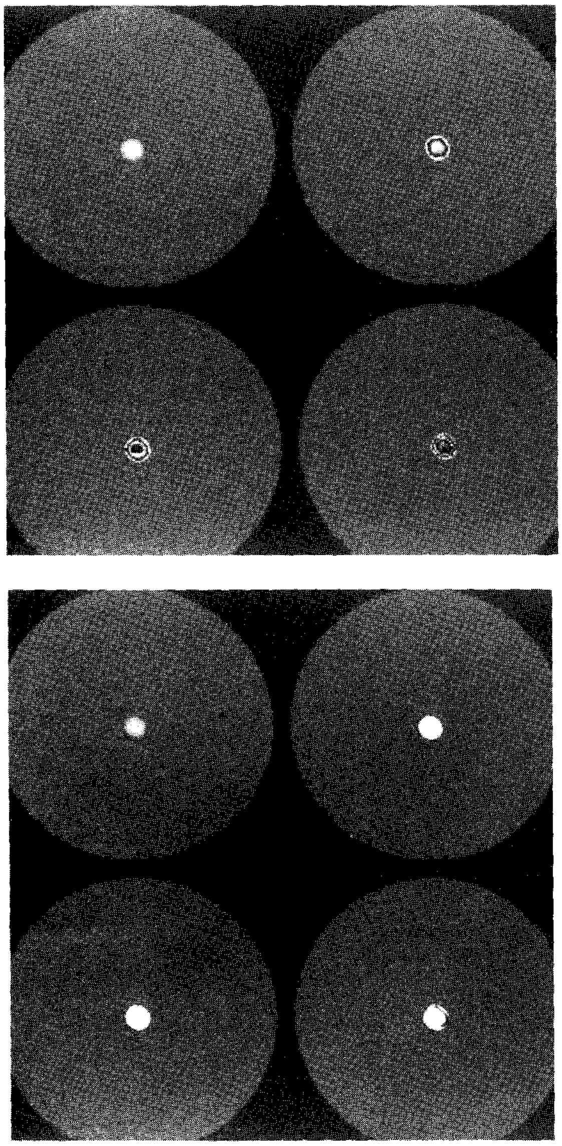


FIG. 6. Background-phase corrected and intensity-masked (that is, noise pixels outside the phantom masked out) phase images of cylindrical phantom filled with stationary water, with central tube containing water flowing at rates increasing from top left to top right to bottom left to bottom right (mean velocities approximately 3–19 cm/s). (A) Conventional subtracted phase images. (B) Images in (A) after phase-wrap correction [same display gray scale as (A)].

large amounts of phase wrap, it can still significantly extend the effective dynamic range of phase imaging techniques, permitting their use with increased sensitivity and thus the measurement of lower velocities. In the example in Fig. 6, the dynamic range is effectively increased from $\pm\pi$ to $\pm 5\pi$ by this unwrapping technique; higher degrees of unwrapping could be achieved with sufficient smoothness of the phase variation. Although we have applied this technique to the phase measurement of velocity, it may also be applicable to other phase measurement techniques.

Other approaches that have been applied to the problem of phase wrapping have required acquiring multiple signals with different degrees of sensitization to phase shift, in order to avoid the ambiguity of phase resulting from wrapping without sacrificing sensitivity.[5] The advantage of the technique we have described here is that it can be applied as a post-processing step after acquiring a single baseline-corrected image.

ACKNOWLEDGMENTS

This work was supported by NIH grant No. RO1-HL33236. L. Axel is an Established Investigator of the American Heart Association, and is supported in part by the Southeast Pennsylvania Chapter.

[1] E. L. Hahn, "Detection of sea-water motion by nuclear precession," J. Geophys. Res. **65**, 776 (1960).

[2] P. R. Moran, "Evaluation of phase modulation-method for NMR true flow imaging," Radiology **149**, 206 (1983).

[3] A. Constantinesco, J. J. Mallet, A. Bonmartin, C. Lallot, and A. Briguet, "Spatial or flow velocity phase encoding gradients in MNR imaging," Magn. Reson. Imag. **2**, 335 (1984).

[4] D. J. Bryant, J. A. Payne, D. N. Firmin, and D. B. Longmore, "Measurement of flow with NMR imaging using a gradient pulse and phase difference technique," J. Comput. Assist. Tomogr. **8**, 588 (1984).

[5] M. O'Donnell, "NMR blood flow imaging using multiecho, phase contrast sequences," Med. Phys. **12**, 59 (1985).

[6] R. E. Wendt III, P. H. Murphy, J. J. Ford, R. N. Bryan, and J. A. Burdine, "Phase alterations of spin echoes by motion along magnetic field gradients," Magn. Reson. Med. **2**, 527 (1985).

[7] P. R. Moran, R. A. Moran, and N. Karstaedt, "Verification and evaluation of internal flow and motion," Radiology **154**, 433 (1985).

[8] V. J. Wedeen, B. R. Rosen, D. Chesler, and T. J. Brady, "MR velocity imaging by phase display," J. Comput. Assist. Tomogr. **9**, 530 (1985).

[9] P. E. Valk, J. D. Hale, L. E. Crooks, L. Kaufman, M. S. Roos, D. A. Ortendahl, and C. B. Higgins, "MRI of blood flow: Correlation of image appearance with spin–echo phase shift and signal intensity," Am. J. Roentgenol. **146**, 931 (1986).

[10] G. L. Nayler, D. N. Firmin, and D. B. Longmore, "Blood flow imaging by cine magnetic resonance," J. Comput. Assist. Tomogr. **10**, 715 (1986).

[11] I. R. Young, G. M. Bydder, and J. A. Payne, "Flow measurement by the development of phase differences during slice formation in MR imaging," Magn. Reson. Med. **3**, 175 (1986).

[12] R. I. Pettigrew, W. Dannels, J. R. Galloway, T. Pearson, W. Millikan, J. M. Henderson, J. Peterson, and M. E. Bernardino, "Quantitative phase-flow MR imaging in dogs using standard sequences: Comparison with *in vivo* flow-meter measurements," Am. J. Roentgenol. **148**, 411 (1987).

[13] R. E. Dinsmore, V. Wedeen, B. Rosen, G. L. Wismer, S. W. Miller, and T. J. Brady, "Phase-offset technique to distinguish slow blood flow and thrombus on MR images," Am. J. Roentgenol. **148**, 634 (1987).

[14] C. L. Dumoulin, S. P. Souza, and H. R. Hart, "Rapid scan magnetic resonance angiography," Magn. Reson. Med. **5**, 238 (1987).