

4D phase-contrast un-aliasing using both phase and magnitude

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TARGET AUDIENCE: Researchers and clinicians in the field of cardiac MRI, specifically, those interested in 4D flow to visualize the entire vascular structure

PURPOSE: Blood flow information can be derived from phase images acquired with 2D and 3D phase-contrast (PC) MRI. Time-resolved 3D PC-MRI, also termed as 4D flow MRI [1], has gained increased interest due to its capability to evaluate 3D hemodynamics in entire vascular structures. Because phase-aliasing occurs when the velocity encoding value (VENC) is lower than the blood peak-velocity, high VENC values are typically selected in clinical practice. While selecting high VENC values is a convenient solution, it is often not optimal because it results in reduced sensitivity to slow flow and may increase scan time if a repeat scan is needed. Alternatively, spatial and temporal phase unwrapping techniques [2-4] can be used to recover true phase from wrapped (aliased) phase images. This abstract addresses a common problem with spatial and temporal unwrapping techniques, which often fail to successfully un-alias 4D phase images because the images are both spatially and temporally under-sampled, i.e., the true phase difference between spatially neighboring pixels or temporal neighboring frames of a single pixel are larger than π . Here we present a newly developed un-aliasing method for 4D flow MRI.

METHODS: The proposed method first performs 3D spatial phase unwrapping [5] of the volume on a frame-by-frame basis. To solve the problem of flow-direction swap caused by spatial under-sampling, the method applies temporal unwrapping from diastole to systole on a pixel-by-pixel basis. First, a reference frame is identified in a pixel's velocity profile as the first frame where a phase jump $> \pi$ is observed. A "cut off" frame is then defined based on the magnitude profile; specifically, the frame with the minimum magnitude value is considered as the "cut-off" frame.

Time-resolved 3D phase contrast data were acquired on a 3T MR scanner. Imaging was performed using a 3D PC-MRI sequence (TR/TE = 5.8/1.7 ms, flip angle = 15, 1.2 mm slice thickness, 256x192 in-plane resolution, 83.33 KHz readout bandwidth, matrix size 256x256x128, 50 cm/s VENC; 70 ms temporal resolution; 20 cardiac phases were reconstructed over the cardiac cycle). Data was processed off-line using MATLAB. While un-aliasing was performed for each flow direction separately only the results in SI direction are shown in this abstract.

RESULTS and DISCUSSION: Representative magnitude and phase images are shown in Fig 1, with phase aliasing clearly observed in the measured phase image (Fig. 1b). A white line is plotted across the superior vena cava and aorta, which represent a challenging area for phase un-aliasing because flow occurs in two directions in neighbouring pixels, making differentiation simply based on spatial phase unwrapping impossible. The change in phase (of the voxels along the white line) over the cycle is shown in Fig 2, with the long and short arrows in Fig. 2b indicating spatial and temporal under-sampling regions, respectively. 3D spatial phase unwrapping alone (Fig. 2c) cannot determine the flow direction in the aorta correctly. This is expected when spatial under-sampling exists. However, the reference-frame can be easily identified from Fig. 2c. Using the magnitude profiles (Fig. 2a) the cut-off frame is easily determined. Use of the magnitude rather than the phase profile to determine the cut-off frame is more robust because a non-trivial threshold value of phase difference between frames is required if the phase profiles alone are used. Fig. 2d demonstrates that the proposed method correctly recovers the velocity direction in a case with both spatial and temporal under-sampling.

Figure 3 reports un-aliased phase images generated using the proposed method. Figure 3a corresponds to Fig 1b and Fig. 3b shows a sagittal slice of the aorta. The results in Fig. 3 demonstrate that most phase-aliased pixels are recovered. Some remaining aliasing is observed near the aortic valve and aortic wall suggesting that further post-processing, such as spatial-smoothing, may be required.

CONCLUSION: Using the temporal variations of the magnitude profile to tackle temporal under-sampling allows aliasing-free 4D flow images to be generated even when the phase contrast data are acquired with a single low VENC (~ 50 cm/s) and low temporal resolution (~ 70 ms).

REFERENCES: [1] Markl et al., 4D Flow MRI, JMRI 36: 1015-36, 2012. [2] Xiang et al., Temporal phase unwrapping for CINE velocity imaging, JMRI 5:529-34, 1995. [3] Yang, et al., Dynamic range extension of cine velocity measurements using motion-registration spatialtemporal phase unwrapping, JMRI 6:495-502, 1996. [4] Salfity et al., Extending the dynamic range of phase contrast magnetic resonance velocity imaging using advanced higher-dimensional phase unwrapping algorithms, Interface 3:415-27, 2006. [5] Liu and Drangova, Intervention-based multidimensional phase unwrapping using recursive orthogonal referring, MRM 68: 1303-1316, 2012.

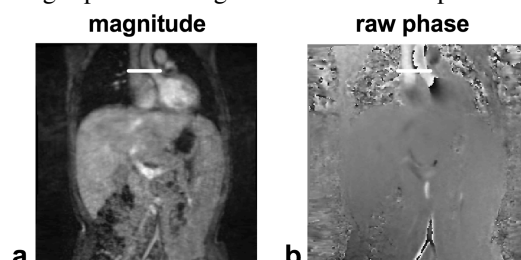


Fig. 1 Representative coronal slice at the 6th frame, velocity-encoding along SI direction. The white line identifies a region of phase aliasing.

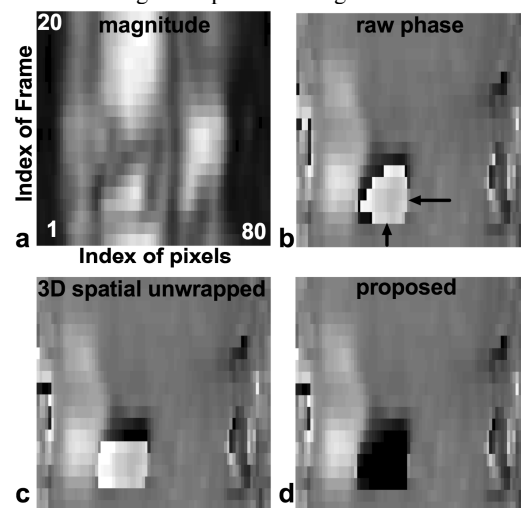


Fig. 2 The temporal profiles of the pixels along the white line defined in Fig. 1.

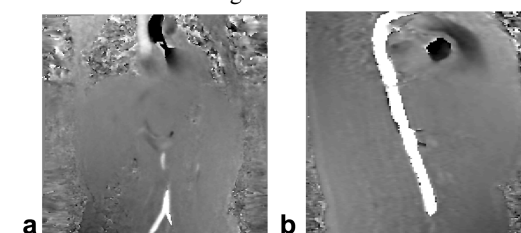


Fig. 3 Examples of un-aliased phase images. (note: the display range is capped at $\pm\pi$)