4D Gradient Based Phase Unwrapping for PC-MR Flow Data

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Introduction: 4D PC MRI has emerged as a promising approach for hemodynamic evaluation of larger vascular territories. One of the major problems associated with volumetric phase contrast MRI is the large dynamic range of velocities of interest and the potential risk of velocity aliasing in areas of higher velocities. While correcting a wrapped voxel is easily accomplished by adding or subtracting multiples of 2π, determining which voxels are wrapped is challenging. There is a large body of research on the phase unwrapping problem, spanning many different imaging modalities and generally following a path-based or least-squares cost function based algorithm [1]. Many of the path-following methods are challenged with regular PC MR data that contain noise, sharp jumps at vessel walls between static and moving spins, or undersampling artefacts in accelerated acquisitions. The vast majority of phase unwrapping algorithms operate in 2 dimensions, with some approaches for processing in 3 dimensions [2], or in the temporal dimension [3], or a combination of 2D and temporal dimension [4]. Here we demonstrate a novel phase unwrapping method that utilizes a gradient approach in 4 dimensions, space and time.

Algorithm: Blood flow through a vessel is inherently continuous in space and time, so as voxel size and temporal resolution approach zero, the gradient between voxels in these directions also approach zero. As voxel size and temporal resolution increase, the gradients involved become larger and the process of differentiating normal flow patterns from those with wrapped phase values becomes more challenging.

The algorithm calculates the probability P_0 that a voxel p_0 is wrapped: $P_0 = \frac{\sum w_i[\emptyset(p_i)-\emptyset(p_0)]}{2\pi \sum w_i}$, where w_i is a weighting factor to be described later, and p_i is the set of neighboring voxels. The probability function also contains information on the direction (positive or negative) that the voxel is wrapped. In this work, p_i is the set of 8 immediate neighboring voxels, two in each x, y, z, and t. If P_0 exceeds an empirically selected threshold, then the voxel phase is unwrapped. This process is repeated for a predetermined number of iterations which grows with the size of the wrapped areas. Additional modifications to this algorithm were implemented for improved performance: **Dual Threshold:** A common problem with a gradient method in phase contrast unwrapping is that voxels in a large wrap area will not be readily identified as wrapped voxels. Even on the edge of the wrapped area, many of the neighboring voxels are also wrapped, thereby lowering the probability value (P). Hence, a low threshold is used to 'break up' wrapped areas, and in a successive path, a high threshold is used to unwrap the data that are now contained in multiple smaller wrapped regions. This is preferable to a single threshold, which if too low will cause errors and remaining checker patterns, and if too high will not detect enough voxels as wrapped. **Masking:** The image volume is masked beforehand based on a complex difference image in order to reduce computational time by including vascular voxels only. In addition, the removal of voxels just outside of the vessel wall benefits the phase unwrapping procedure because these voxels would lower P_0 for wrapped voxels if they were included. **Temporal Weighting:** Often the algorithm can be improved by increasing the weighting factor w_i when calculating the difference along the temporal dimension. Assuming that there are no large jumps in phase throughout the cardiac cycle for a given voxel is generally a safe assumption at the temporal resolution we are working with.

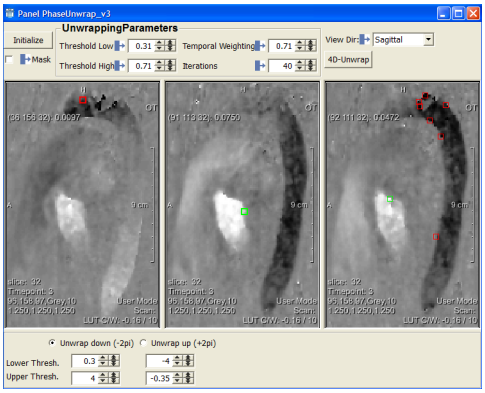

Figure 1: User interface for reviewing phase data, controlling the 4D gradient unwrap process, and manually unwrapping areas with a simple region growing based approach. This image shows an unwrapped ascending and descending aorta where many edge voxels had to be manually corrected.

Methods: Images were acquired on clinical 1.5T and 3T systems (GE Healthcare, Waukesha, WI) after obtaining IRB approval and written informed consent from all subjects. For proper 4D gradient phase unwrapping, 4D PC MR data of high spatial and temporal resolution are required. A 3D radially undersampled trajectory (PC VIPR) [5] was used for acquisitions in various vascular territories including the chest, abdomen, and head. Typical scan parameters were: 0.7-1.3 mm3 isotropic spatial resolution, cubic field of view: (20-32 cm)^3, 15-20 cardiac phases reconstructed with temporal filtering, scan time 5-6 min (10-11 min with respiratory gating), VENC = 40-100 cm/s. The algorithm was implemented using MevisLab (MeVis Medical Solutions AG and Fraunhofer MEVIS, Bremen, Germany) to provide a fast and user friendly interactive platform. Thresholds, time weighting, and the number of iterations as well as reslicing, window leveling and zooming could be performed on the fly. Images were analyzed qualitatively for the areas that could be unwrapped and the nature of unwrapping failures. In particular challenging situations where residual phase wraps remained, manual corrections were performed interactively. The control of both the gradient unwrapping and the manual corrections is handled in a single GUI seen in Figure 1.

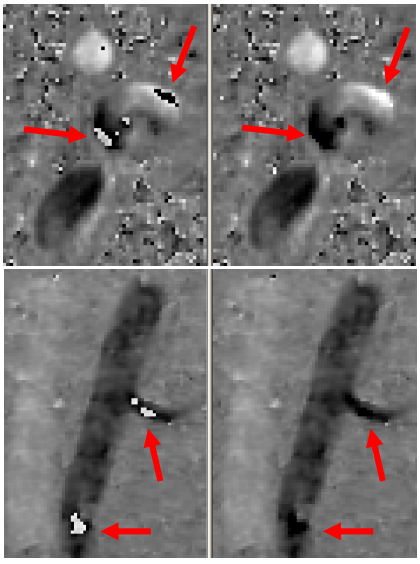

Figure 2: Phase images before (left column) and after (right column) successful automatic phase unwrapping of the jugular vein (top) and of the abdominal aorta and renal artery (bottom).

Results: The algorithm was successfully used in all vascular territories. Fig. 2 shows unwrapping results for a cranial and a renal case. Optimal parameters for robust performance were found to be: low threshold = 0.32, high threshold = 0.75, temporal weighting = 2.5, number of iterations = 100. The automated unwrapping algorithm failed when (i) the highest velocity exceeded twice the venc, (ii) when the wrapped area took up the entire vessel and (iii) when temporal gradients were compromised by phase wraps between the first and second cardiac phase. Another area of failure was seen along vessel walls, where partial volume effects decrease the local gradient for those wrapped voxels. In those regions, manual phase unwrapping was performed from the same platform. The algorithm was not seen to make any wrapped areas worse.

Conclusion: Our study shows that the gradient based method to enforce a continuous flow field in four dimensions allows for reliable phase unwrapping of PC-VIPR data sets. Currently, user interaction is required to define thresholds and the temporal gradient weighting based on vascular territory and noise level. While ideally no user interaction would be required, we believe that a human confirmation and potential manual intervention for wrap-free velocity data will be part of a clinically usable 4D PC MR analysis platform for years to come. Overall, this algorithm performed well for mild to moderate wrapping, and failed for cases with extreme, whole vessel wrapping. Such wraps occurred in cases where the acquisition was optimized for generating non-contrast enhanced MR Angiography (NCE MRA) data and should not occur in acquisitions targeted for hemodynamic analysis. The availability of this phase unwrapping platform allows us to (i) correct for unexpected high velocity regions such as jets, (ii) reduce the acquisition venc to subpeak velocities to provide flow data with higher velocity-to-noise ratios (VNR), and to (iii) generate better quality NCE MRAs with an increased SNR.

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