Echo-planar 3-dimensional cine 3-directional flow imaging of the entire heart

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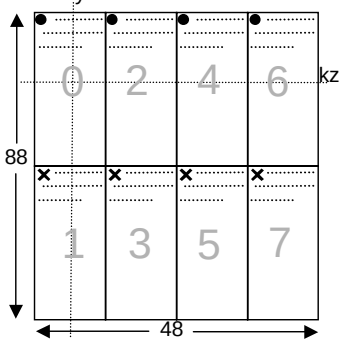
Introduction: The patterns of flow in the heart and great vessels contain information about heart function, with more obvious applications such as valve deficiencies and congenital abnormalities. Routinely acquiring, displaying and sifting relevant features from the vast total amount of flow data remains a distant prospect. Cine phase-contrast velocity mapping is commonly used to acquire 2D-slices with single or multiple velocity-encode directions, requiring skilful positioning and application to acquire whatever is judged to be the most relevant small fraction of the flow data for the particular clinical enquiry. Even experienced operators are often concerned after the patient appointment that a better acquisition might have been possible. Acquiring the entire flow data would simplify this "run-time" judgment, as well as enabling research applications supporting computational fluid dynamics. Phase-contrast velocity mapping has been used to acquire the entire data, generally by using segmented-spoiled-gradient-echo imaging (1). The higher SNR option of SSFP imaging has limited applicability in velocity mapping. Because echo-planar imaging improves acquisition efficiency, a 3D-EPI method adapted for cardiac flow (2) is evaluated for whole-heart 3D 3-directional cine ("7D") flow imaging, aiming to improve the long scan duration and limited spatial and temporal resolution. The method in (2) has apparently been implemented only at 0.5T with slower gradient systems than many modern scanners.

Fig.1



Method: After 130mm slab-selective excitation, 8 echoes were acquired in 10.7ms, one into each of 8 sections of the two phase-encoded dimensions of ky, kz rawdata (Fig 1) of 88 by 48 echoes. Each echo collected 128 kx samples (along lines perpendicular to the page). Even echoes (dots, kx sampling moving towards reader) were used for the upper ky sections and odd echoes (crosses, kx sampling moving away from reader) for the lower ky sections. On subsequent cardiac cycles the entire sampling path was shifted along kz then ky (dotted line in each section) so that after 12x44 accepted cycles of data acquisition it completely filled all the sections. The raw data coverage was offset so that the first echo was used to collect the central raw data, for minimal velocity phase errors in the kentral raw data. To smooth out EPI flow ghosting of frequency-encode flow (kx) caused by the odd/even phase difference (PI/2 at 1.8m/s) between the upper (0,2,4,6) and lower (1,3,5,7) sections, a sliding frequency-encode velocity phase compensation was added as a function of ky (2), resembling gradient moment smoothing of the phase-encode axis (3). Imaging of flow along the frequency-encode and the two phase-encoded axes was tested by flow phantom experiments at 1.3m/s; the short readout minimized distortion and the central velocity compensation minimized signal loss. No other sliding acquisition window temporal compensation was applied.

In five volunteer subjects, an oblique slab was positioned from end-expiratory breath-hold pilots, to enclose the entire heart in acquisition volume 350mm (frequency-encode) along the heart's long axis (1.5m/s venc) by 241mm by 130mm (primary and secondary phase-encodings across the short-axis, both 1m/s venc) for 2.7mm cubic voxels. Within each cardiac cycle, each 50ms cine repetition included all 3 velocity-encodings and the reference with TR=12.5ms. In the absence of contrast agent, 10° flip angle was used. In each cardiac cycle, following data acquisition for the cine frames, a respiratory navigator was acquired through the right diaphragm. Data was accepted when respiratory position lay within an 8mm range at the end-expiratory limit of normal breathing. Velocity maps were reconstructed by phase image subtraction with concomitant gradient correction (4) and subtraction of a background phase correction acquired using each subject's in-vivo sequence parameters and positioning on a phantom tank. No gradient non-linearity correction (5) was made. Image voxel interpolation or filtering were not applied.

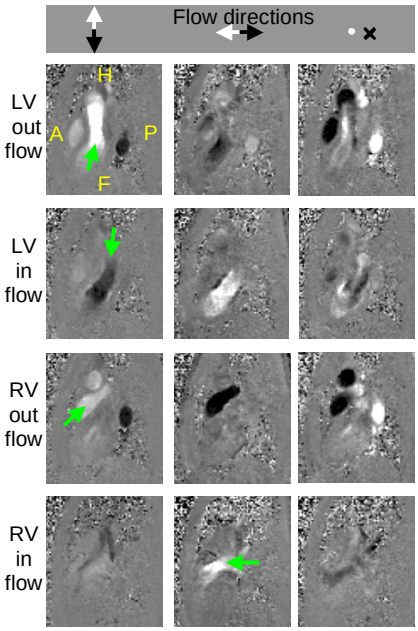


Fig.2: Oblique-sagittal 2.7mm slices of cardiac and great-vessel flow.

Results and Discussion: In all subjects, flow patterns were visualized through systole and early diastole in all of the heart chambers and great vessels to its base, for example circulating inflow in the ventricles and helical flow in large arteries. Left and right ventricular outflow and filling were identified (Fig 2), and further analysis and quantification of the flow data requires improved software methods (eg 6). Although magnitude image SNR was uniformly low without fresh-inflow enhancement, there were no regions of complete signal saturation in slow-moving blood. No flow-related signal loss was observed in the reference images in the normal volunteer subjects. Full diastolic coverage is sought with the use of retrospective ECG gating. No respiratory artifacts were seen at 40-50% acceptance efficiency with 12-18 minute scan time also depending on heart-rate. More advanced respiratory control methods would counter the problem of respiratory drift, though this was not found to be a major obstacle in these subjects. For shorter imaging time, a 2D-selective RF pulse might replace the slab selection for "inner volume" reduction of the primary PE FOV. For the heart, a 50% reduction could be envisaged, albeit with an SNR loss which is barely affordable without contrast agent. The longer 2D-selective than slab RF select would make the overall time saving marginal unless the ky FOV is reduced by more than 50%, unless respiratory motion-tracked volume acquisition could be applied to approach 100% respiratory motion acceptance. Other options include the shared-phase / UNFOLD approaches, and the SNR behaviour of these are perhaps better with more concern over temporal smoothing of flow variations. Further applications include post-infarct ventricular remodeling, and whole aorta flow measurements.

Conclusions: The volume EPI method is a reliable efficient approach to complete flow acquisition in the heart and great vessels in a practicable acquisition time.

References:

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