2.5D Flow MRI: 2D phase-contrast of the tricuspid valvular flow with automated valve-tracking

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Synopsis

Tricuspid regurgitant velocity is a crucial biomarker in identifying pressure overload in the right heart, associated with diastolic dysfunction and pulmonary hypertension. 2D phase-contrast cannot quantify this flow, and echocardiography is used clinically. We developed a phase-contrast method which utilizes deep-learning algorithms to track the valvular slice in a cardiac phase-dependent manner, which we call 2.5D flow. We studied its performance in nine healthy subjects and patients with tricuspid regurgitation. RV stroke volumes correlated better to forward flow volumes by 2.5D flow vs. static 2D phase-contrast (ICC=0.88 vs. 0.62). 2.5D flow characterized regurgitation in a patient.

Introduction

Valve diseases are an important cause of morbidity and mortality[1]. Specifically, tricuspid valve (TV) regurgitation can be detected in 80% of the general population and considered pathological (moderate or severe) in 15%[2]. Tricuspid valvular regurgitation is often due to elevated right ventricle (RV) pressure, commonly seen in pulmonary hypertension (PH)[3] and patients with diastolic dysfunction, where tricuspid regurgitant velocity is one of 4 criteria used to identify dysfunction (along with LA volume, E/e' and E/A)[4]. Thus, evaluation of tricuspid regurgitant velocity is clinically highly important. A recent study[5] of diastolic dysfunction by MRI, used vorticity duration as a stand-in for tricuspid regurgitant flow, highlighting the need for its evaluation. According to the current ACC/AHA guidelines, TV regurgitation is assessed with a comprehensive transthoracic echocardiography (TE) imaging with Doppler interrogation[1] of blood velocities. Cardiac MR is considered more accurate for mitral and tricuspid regurgitant volumes, using indirect evaluation by subtraction of RV (or LV) stroke volume (S) from pulmonary artery (PA) or Aortic (Ao) forward flow[6,7]. However, direct valve flow evaluation by cardiac MRI is not feasible due to valvular displacement during the cardiac cycle; even more so for the highly dynamic (translating and rotating) TV[8]. 4D flow methods have had success in tricuspid regurgitant velocity evaluation, using many minutes of scan time, because retrospective valve tracking can be employed[9,10]. Prospective valve-tracking methods have been employed to acquire 2D phase-contrast (PC) with a dynamic slice plane prescription that changes over the cardiac cycle[11,12]. We recently used this approach, but using modern feature-tracking of the mitral valve[13] to enable rapid and accurate valve-tracking of the simple mitral valve translations[14]. Even so, to obtain accurate displacements and valvular velocities (needed to correct flow values) often required expert, tedious, and time-consuming manual annotations. More recently, we have developed deep-learning algorithms to fully-automatically track both the mitral valve, MVnet[15], and also tricuspid valve insertion points, TVnet[16,17], with the TV exhibiting greater motion including rotation vs. the mitral valve. In this study, we utilize a 2D PC sequence, with dynamic slice-prescription based on automatic tracking in 2- and 4-chamber RV cines[18] to determine phase-dependent slice translation and rotation, for prospective valve-tracking PC. This PC approach is called 2.5D PC because of the partial 3rd dimension.

Methods

Figure 1 shows the workflow for 2.5D PC. First, RV 2 and 4 chamber cines are acquired and exported to an offline computer for automated tracking of the valve-insertion points, using TVnet. This automated tracking produces the center point of the TV

plane and it is the normal to the TV plane for each time-point in the cardiac cycle. This is automatically input to the customized MRI sequence via a USB device. During the breath-hold, the slice geometry is updated by the sequence at each cardiac phase to match the valve position and orientation. Nine healthy volunteers (36±16y, BMI of 24.9±3.8, 4 females) underwent a cardiac MR (3T Siemens, Erlangen, Germany) that included a standard 4-chamber cine and the less common RV 2-chamber cine, both used for automated valve-tracking by TVnet. The study was approved by our local IRB and all subjects provided informed signed consent. The 2D-PC scan protocol for the TV was: FOV: 380mm, acquisition matrix=256×208, repetition time=5.3ms, echo time=3.4ms, flip angle=15°, voxel size= 1.48×1.48×5-6 mm3, GRAPPA=2, partial Fourier 6/8, through-plane flow-encoding with a VENC of 100cm/s to 150cm/s; temporal resolution of 42ms. This acquisition was performed for a static TV plane coinciding with the valve plane in late-systole and with a dynamic valve-tracking. Standard planimetry of the cine stack yielded SVs, and standard PA and Ao PC were performed to compare resultant SV values. PC analysis was done using Segment software[19], including eddy current compensation, using cardiac phase dependent ROIs to identify static tissue. The flow velocities were corrected for relative motion of the valve[20], on a pixel by pixel basis, for both static and 2.5D PC flow evaluation.

Results

Figure 2 shows a tricuspid flow curve, presenting the flow by PC for the static plane, and the valve-tracking PC. The valve-tracking plane yields a more physiological curve in general, with mainly zero flow in systole, when the valve is shut and flow peaks in diastole corresponding to the E and A wave. 2.5D PC forward flow compared well to stroke volumes by planimetry (RVSV, ICC=0.88, bias ± 2SDs of -2.5 ± 6.3mls, Figure 3B; PA flow, ICC=0.72, bias ± 2SDs of -5.1 ± 15.9mls; LVSV and Aortic flow also agreed well), as expected in healthy subjects. As shown in Figure 3, both static and 2.5D PC were well correlated to RVSV when corrected for relative velocities of the valve, but the 2.5D PC showed a slope closer to unity, a smaller bias, and a much stronger ICC. Figure 4 shows the performance of 2.5D PC in a patient with regurgitation.

Conclusion

The 2.5D PC method was validated for forward flow, with performance similar to that reported for 4D flow techniques[9,10], and it accurately follows the tricuspid valve. Further studies in patients with regurgitation are needed to define 2.5D PC's ability to detect regurgitant jets.

Acknowledgements

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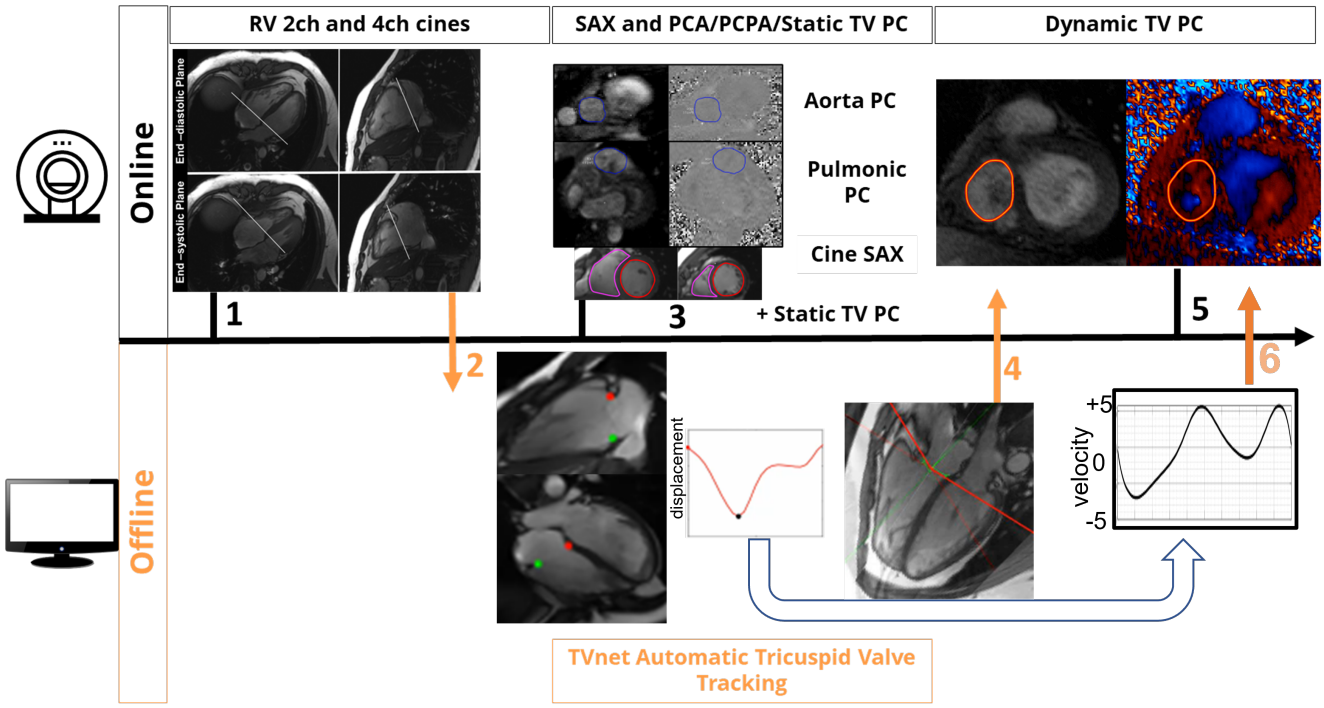

Figure 1. 2.5D workflow. Showing 1) acquisition of RV 2ch and 4ch, 2) automated valve tracking analysis offline. 3) Meanwhile, other acquisitions can be acquired such as Aortic and PA flow, and a short-axis cine stack, for comparisons of stroke volume. 4) Tracking information is sent to the MRI sequence via USB device, followed by 5) dynamic 2.5D PC acquisition. 6) To obtain blood velocity (relative to the valve), the valve plane velocity must be subtracted.

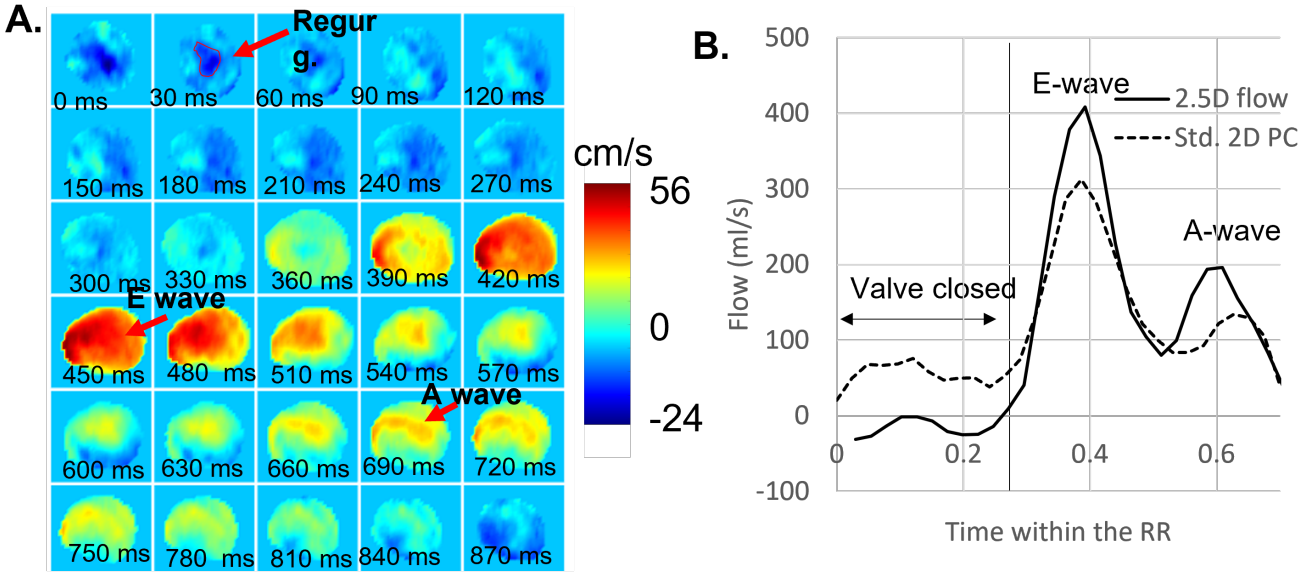

Figure 2. Valvular flow in a healthy control. A) Flow maps and flow curves (B) showing an E and A wave in diastole, and minimal flow in systole.

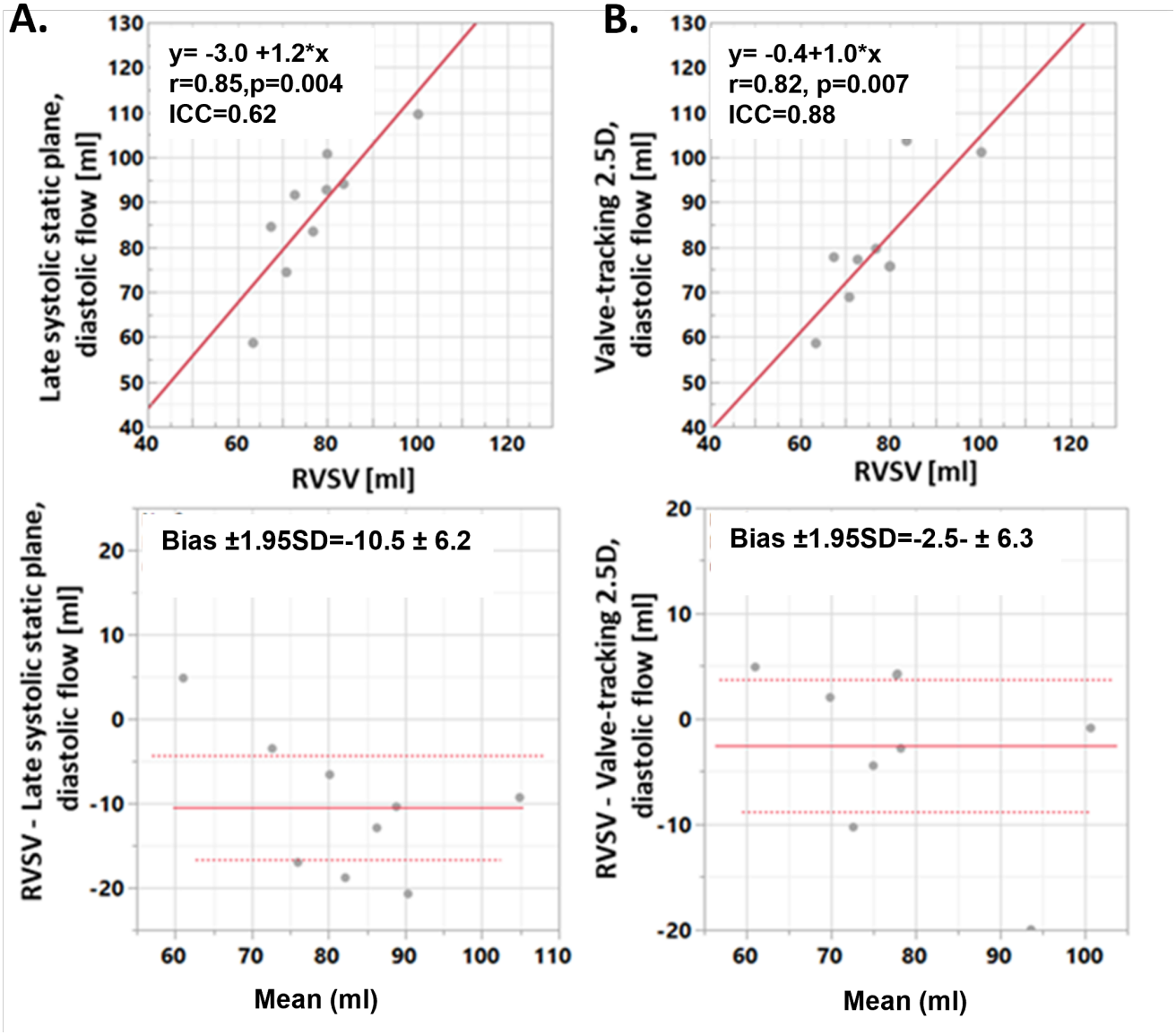

Figure 3. RV Stroke volume (RVSV) is compared to diastolic forward flow volume in healthy subjects by A) static PC with slice plane coinciding with the valve plane at end-systole, and B) 2.5D valve-tracking PC, prescribed at the valve plane. The flow values were corrected for both eddy currents and for relative valvular velocities. Both methods showed excellent correlation to RVSV, but 2.5D flowed exhibited lower bias and variability, and a slope closer to unity. This was reflected by an excellent ICC for valve tracking 2.5D PC vs. RVSV.

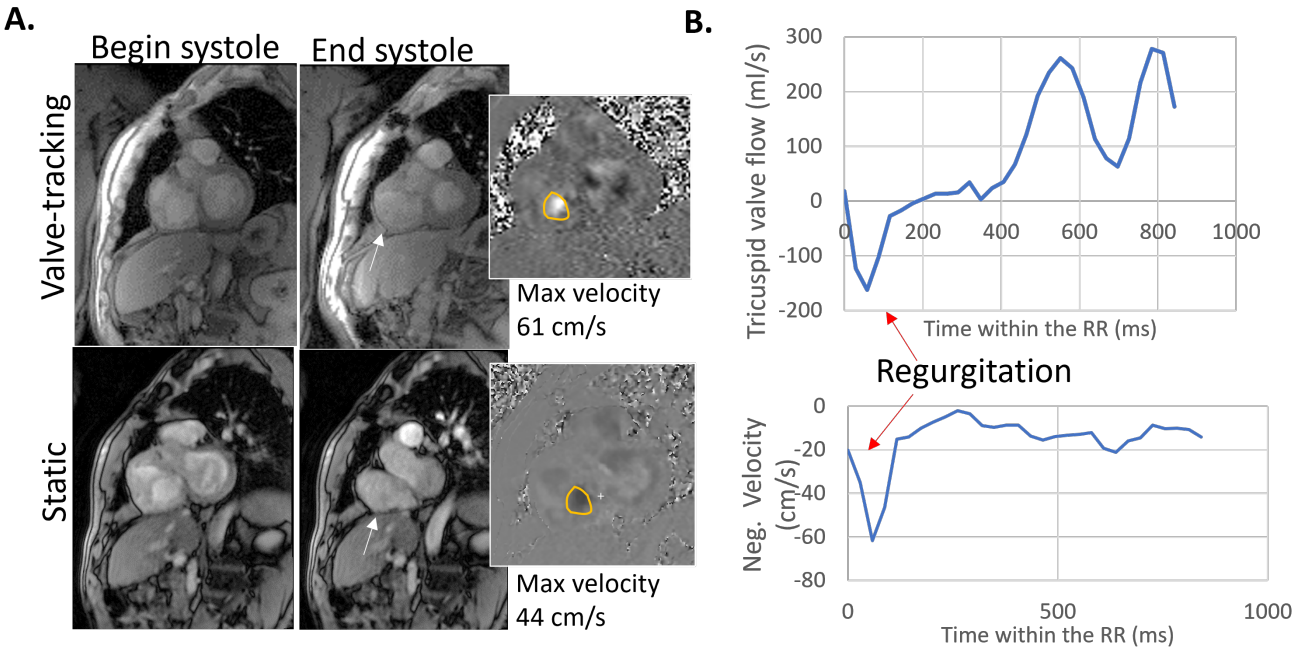

Figure 4. A) Tricuspid flow in patient with regurgitation comparing static and 2.5D valve-tracking flow (both planned just below the valve at begin-systole). This patient was observed in early systole to have a high velocity jet. Note that the static slice shows the right atrium in end-systole, while the 2D.5D flow maintains the valvular position. B) 2.5D flow in the patient shows a regurgitant flow and negative regurgitant velocity in early systole.