Reconstruction of variable-density data in Fourier velocity encoding

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Introduction: Fourier velocity encoding (FVE) [1] is useful in the quantitation of valvular stenosis and regurgitation, as it overcomes partial-volume effects that may cause loss of diagnostic information in phase-contrast imaging [2]. Velocity resolution (v_{res}) can be improved using variable-density sampling along the velocity dimension (k_v) [3], but considerable aliasing artifacts arise when a density reduction factor (ρ) greater than 2 is used with conventional reconstruction methods such as gridding [4] and DrFT [5]. We propose k_v-FOCUSING (FOV Centering Using Sinc INterpolation), a reconstruction scheme that eliminates artifacts caused by variable-density sampling for typical valvular flow distributions. Phantom and in vivo validation was performed using one-shot FVE [3] and spiral FVE [6] acquisitions.

Theory: k_v-FOCUSING combines variable-width sinc interpolation along k_v with velocity field-of-view (v_{FOV}) centering. Variable-width interpolation [7] reduces artifacts by trading v_{res} for v_{FOV}. This is desirable, as plug flow contains high-frequency components in k_v, but occupies only a small portion of the v_{FOV}, whereas flow jets fill a wider portion of the v_{FOV} but require lower v_{res} (Fig. 1). This approach maximizes v_{res} at the center of v_{FOV} (Fig. 2). Thus, the v_{FOV} is shifted towards the center of the distribution by applying a linear phase to the sinc kernels. Reconstruction is performed independently for each time-frame. Conventional gridding and k_v-FOCUSING can be represented as follows.

Conventional gridding:

$$\zeta(k_v) = \sum_n w_n S_n \psi(k_v - \kappa_n)$$

k_v-FOCUSING:

$$\zeta(k_v) = \sum_n w_n S_n \psi_n(k_v - \kappa_n) e^{-j2\pi(k_v - \kappa_n)v_o}$$

S_n: sample of $S(k_v)$ taken at $k_v = \kappa_n$
$\zeta(k_v)$: reconstructed estimate of $S(k_v)$
w_n: density compensation function
$\psi(x)$: constant-width convolution kernel
$\psi_n(x)$: variable-width windowed sinc kernel
v_o: center of distribution, estimated from S_n

Methods: To determine an appropriate value of ρ for k_v-FOCUSING, we performed simulations using numerical models of the velocity distribution in plug flow and in stenotic and regurgitant flow jets. The method was experimentally validated using one-shot FVE in a flow phantom with a wide distribution of velocities, and using spiral FVE to examine aortic valve flow in a healthy volunteer.

Results: Numerical simulation results suggest that $\rho = 4$ may be used to image plug flow and flow jets, with no significant artifacts (Fig. 3). In the *in vivo* validation (Fig. 4), the velocity resolution in spiral FVE was improved from 86 cm/s to 33 cm/s using variable-density sampling (160% improvement compared to uniform sampling). Phantom results using one-shot FVE are shown in Fig. 5. A quantitative evaluation is presented in Table 1.

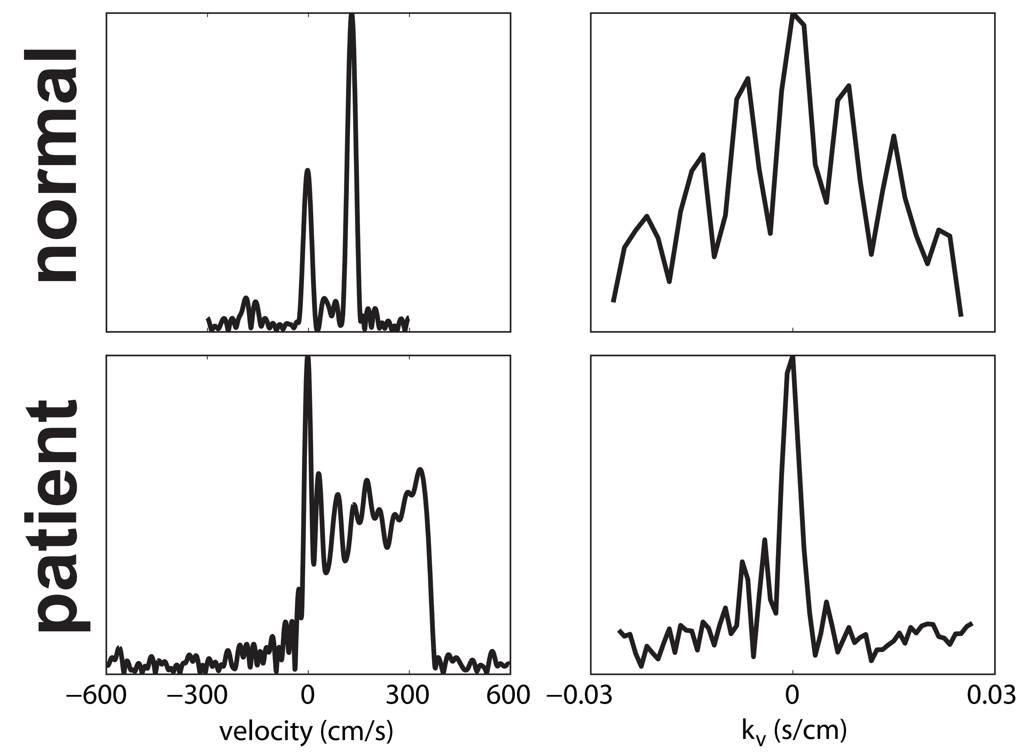

Figure 1: Typical (measured) velocity distributions (left) and correspondent k-space representation (right). Data obtained using spiral FVE with uniform-density sampling, in a healthy volunteer (top) and a patient with aortic stenosis (bottom). Plug flow contains high-frequency components in k_v, but occupies only a small portion of the v_{FOV}. Flow jets fill a wider portion of the v_{FOV} but require lower v_{res}.

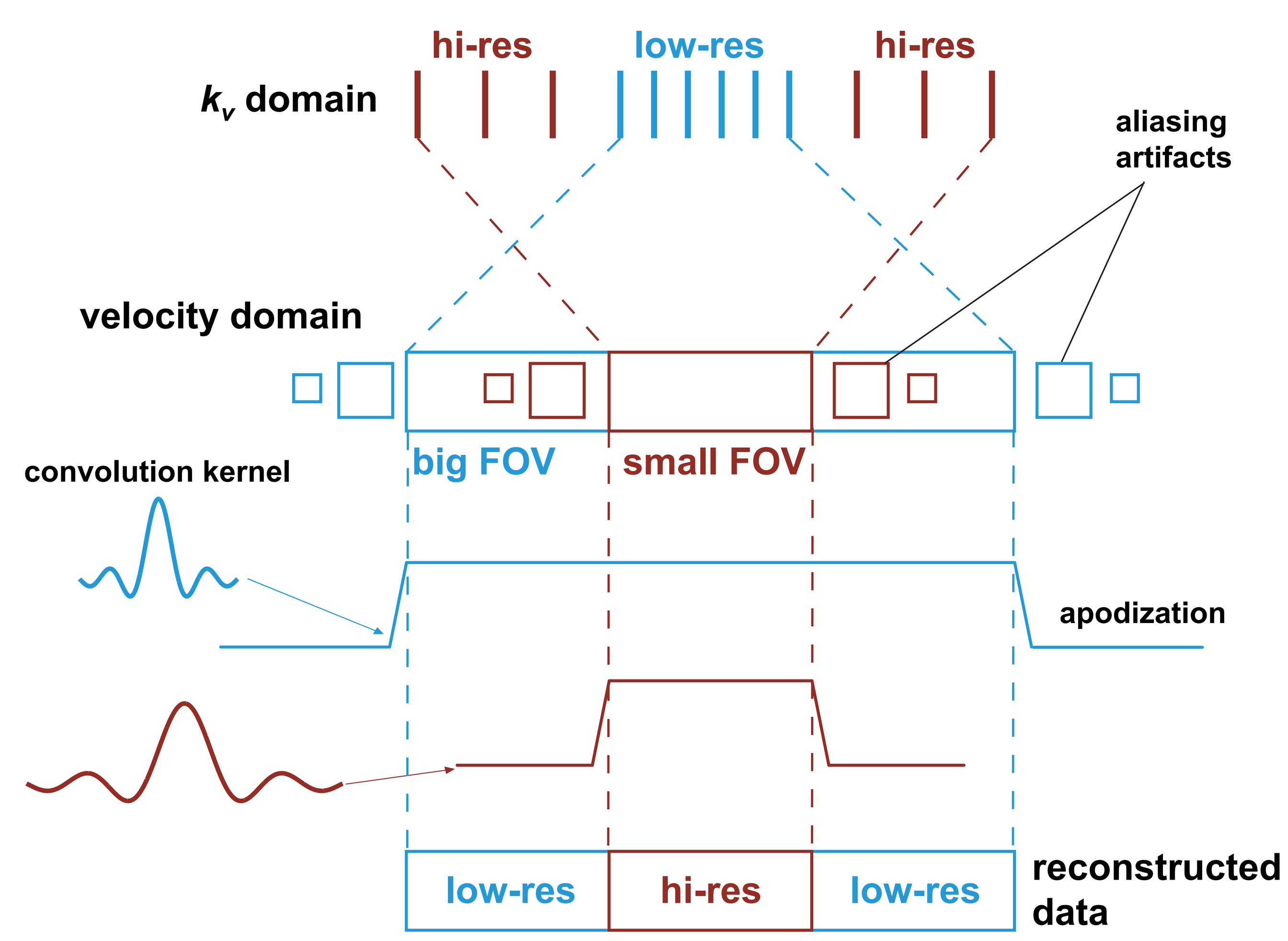

Figure 2: Variable-width sinc interpolation diagram. High-resolution components are more sparsely sampled then low-resolution ones, resulting in a smaller unaliased velocity FOV. Using a sinc kernel of appropriate width for each k-space sample, the resulting apodization function filters the corresponding aliasing. The velocity resolution in the reconstructed data varies across the velocity FOV.

Conclusions: Variable-density sampling along the velocity dimension was used to improve the resolution in FVE by up to 160%. Artifacts were reduced using a novel reconstruction scheme (k_v-FOCUSING), which was validated using numerical simulations and a flow phantom, and *in vivo*, with both spiral FVE and one-shot FVE. In spiral FVE, k_v-FOCUSING allows 2.6-fold reduction in breah-hold duration. In one-shot FVE, it provides improved temporal resolution and reduced off-resonance effects. k_v-FOCUSING can potentially be applied to any FVE method that utilizes variable-density sampling, requiring no modification to the imaging pulse-sequence.

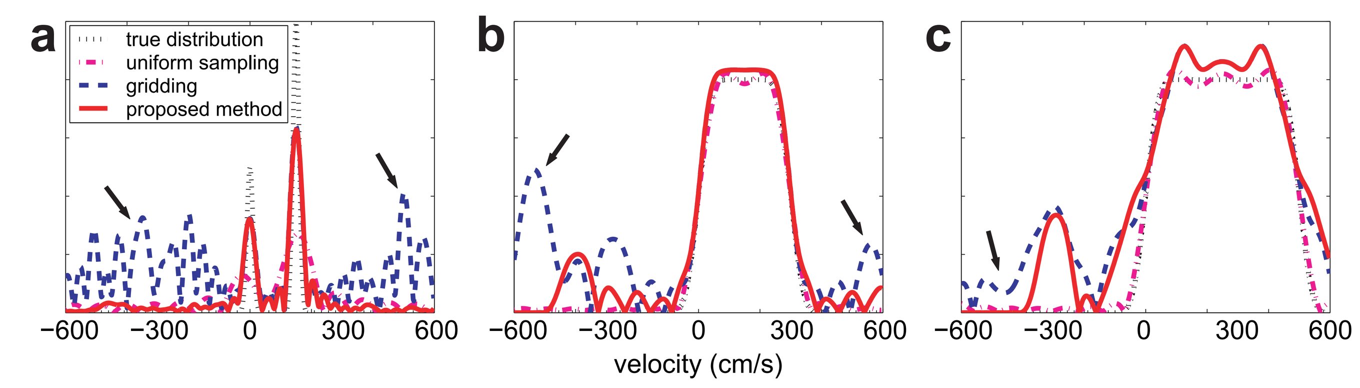

Figure 3: Numerical simulations results: (a) simulation of plug flow and static tissue; (b) simulation of a flow jet; (c) simulation of a flow jet with higher peak velocity. The proposed method reduces undersampling artifacts considerably (arrows), especially for narrow and moderately broad distributions..

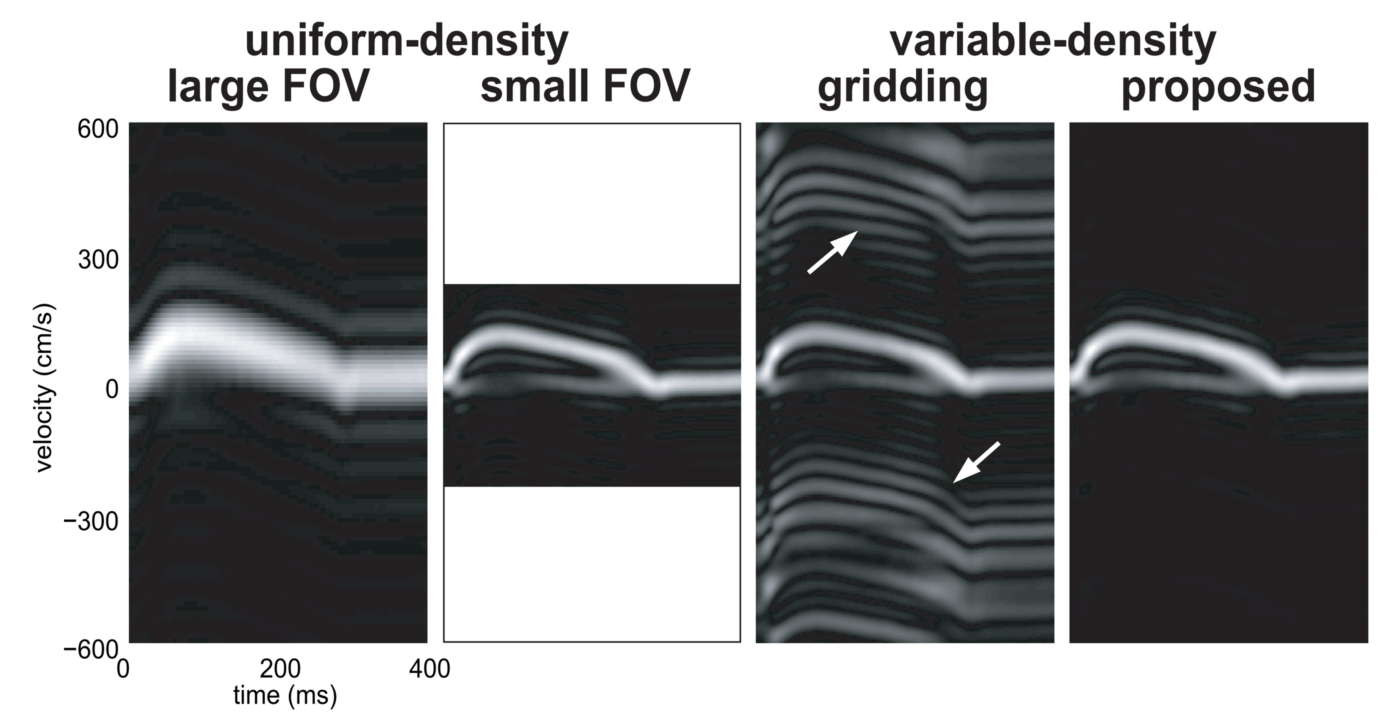

Figure 4: *In vivo* validation of k_v-FOCUSING, using spiral FVE (aortic valve flow, healthy volunteer). k_v-FOCUSING reduces undersampling artifacts (arrows), and provides velocity resolution equivalent to the small FOV uniform-density reference.

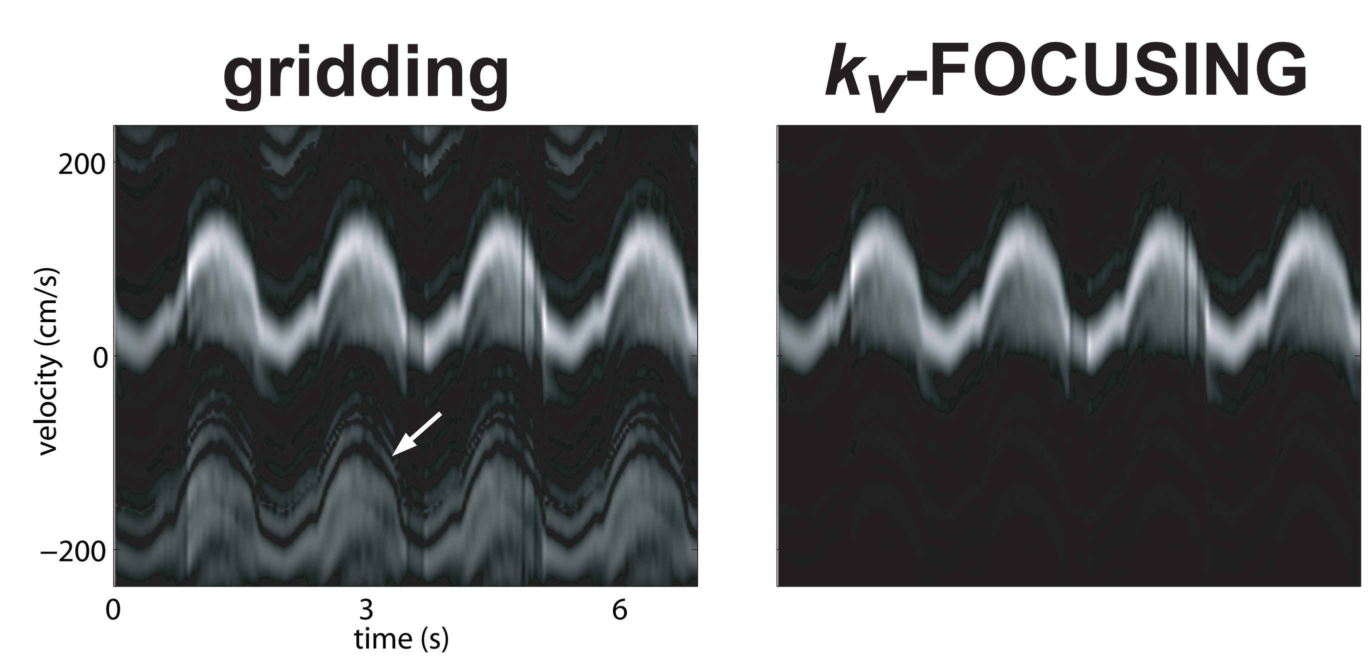

Figure 5: Evaluation of k_v-FOCUSING, using one-shot FVE (pulsatile flow phantom). Undersampling artifacts are significantly reduced with the proposed method.

Table 1: Variable-density FVE signal-to-noise ratio (dB) comparison with a uniform-density reference..

	Simulation: Plug flow with static tissue	Simulation: Narrow distribution	Simulation: Broad distribution	*In vivo* Healthy volunteer
Conventional gridding	-1	7	10	0
Proposed method	17	15	11	14

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