Low Rank and Sparse Decomposition of Ultrasound Color Flow Images for Suppressing Clutter in Real-Time

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In this supplementary material, we report a schematic diagram of the set-up for the phantom experiment (Fig. 1). In addition, we represent an analysis to show the dependence of the optimal tunable parameters of SVD on the noise level (Fig. 2). Finally, we present a comparison among the power Doppler images obtained from SVD, HOSVD [1] and RAPID (Fig. 3).

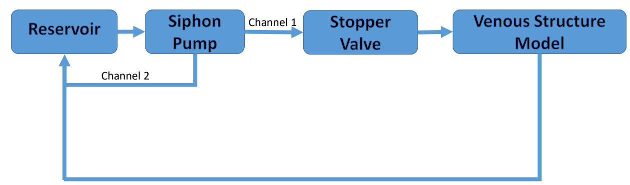
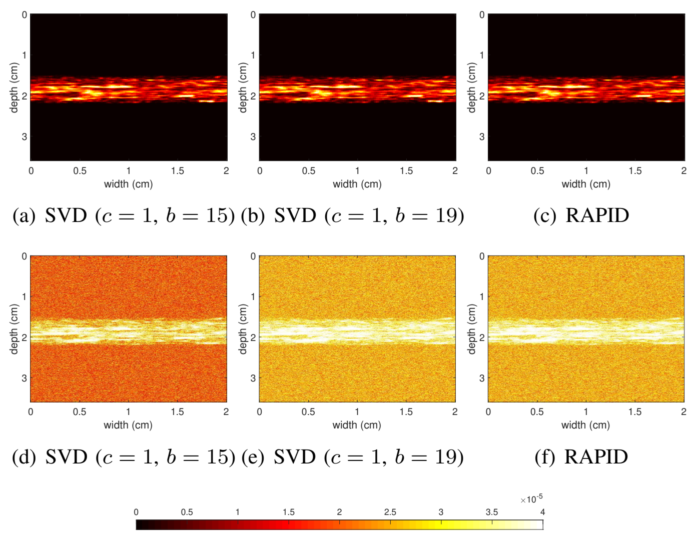


Fig. 1: A schematic depiction of the set-up for the phantom experiment.

I. Results

Fig. 1 shows the schematic description of the set-up for the phantom experiment.

Fig. 2 represents the power Doppler images from SVD and RAPID for the simulation data with added random noise of uniform distribution. Two levels of noise with Peak Signal-to-Noise Ratio (PSNR) values of 58.43 dB and 39.34 dB are added to the envelopes of RF data. It is evident from Fig. 2 that the result from SVD for blood rank 15 is similar to that of 19 in case of the lower noise level. On that other hand, the results from SVD for blood subspace ranks 15 and 19 are substantially different from each other for the higher level of noise. This study indicates that the optimal values of tunable parameters of SVD are highly dependent on the noise level. On the contrary, RAPID automatically obtains the optimal result regardless of the level of noise.



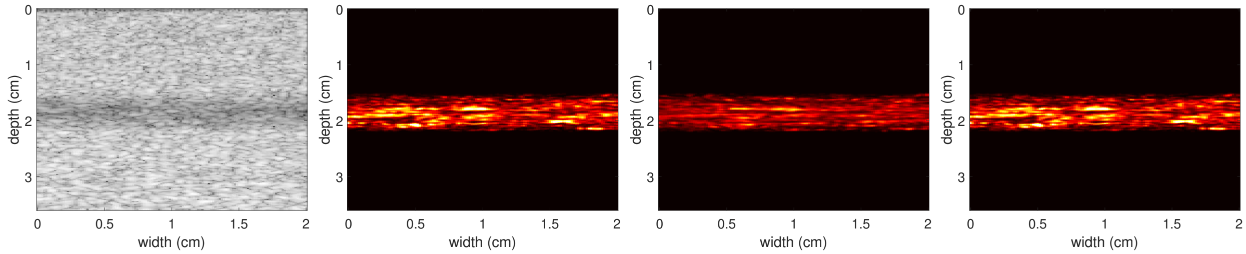
(a) SVD ($c = 1$, $b = 15$) (b) SVD ($c = 1$, $b = 19$) (c) RAPID

(d) SVD ($c = 1$, $b = 15$) (e) SVD ($c = 1$, $b = 19$) (f) RAPID

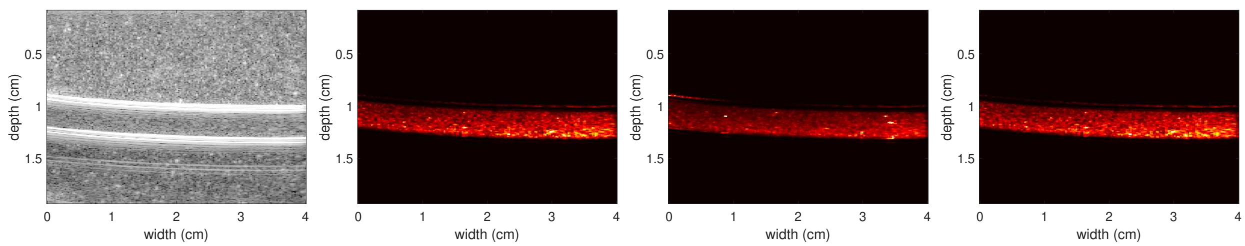
(g) Color bar

Fig. 2: Power Doppler images for simulation with different noise levels. Rows 1 and 2 correspond to PSNR values of 58.43 dB and 39.34 dB respectively. Columns 1 and 2 show results from SVD for different combinations of subspace ranks. Column 3 represents the results from RAPID. (g) shows the color bar.

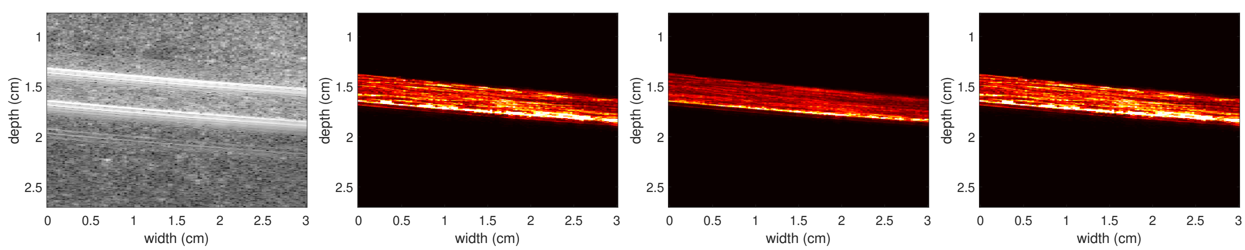
Fig. 3 depicts the clutter suppressed power Doppler images for simulation, phantom and *in-vivo* data sets generated by SVD, HOSVD and RAPID. We have incorporated 15 Radio-Frequency (RF) frames to generate the power Doppler images from SVD and RAPID. We consider a data tensor consisting of 3 matrices where each matrix is an ensemble of 15 slow time frames. For SVD and HOSVD, the best results obtained by careful tuning of the parameters are reported. RAPID converges to the optimal results without the need of any manual tuning. The results from SVD and RAPID are very similar to each other. HOSVD does not seem to improve the quality of the power Doppler images for the datasets used in this study. However, HOSVD is expected to improve the result when a large number of data matrices consisting of more slow time frames are incorporated to form the data tensor. Therefore, it is suggested that HOSVD improves the result at the expense of extensive amount of data. Besides, this method suffers from much higher running time than SVD and RAPID. To be precise, our MATLAB implementation of HOSVD takes more than 40 minutes to execute for a tensor of 3 matrices each of which consists of 15 slow time frames of size 250×125. On the other hand, both SVD and RAPID take less than 1 second to process the same amount of data. Another limitation of HOSVD is that it has 6 tunable parameters and there is no rigid criterion to select the optimal set of values for them. Hence it is very difficult to obtain the optimal result while dealing with a large dataset since it is subject to the manual tuning of 6 parameters over a certain range. This drawback calls the clinical usefulness of HOSVD into question.



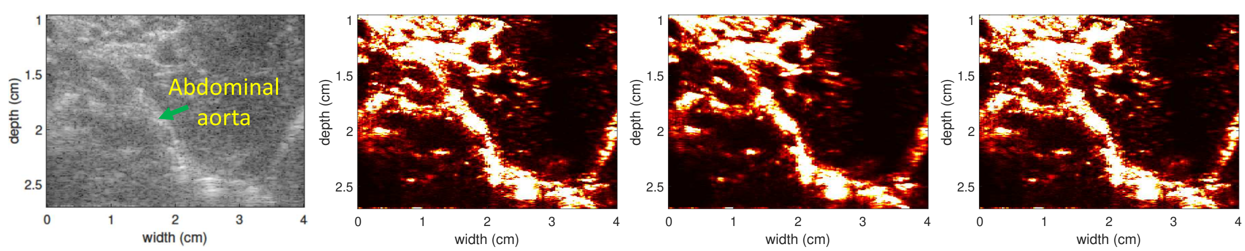
(a) B-mode (b) SVD (c) HOSVD (d) RAPID



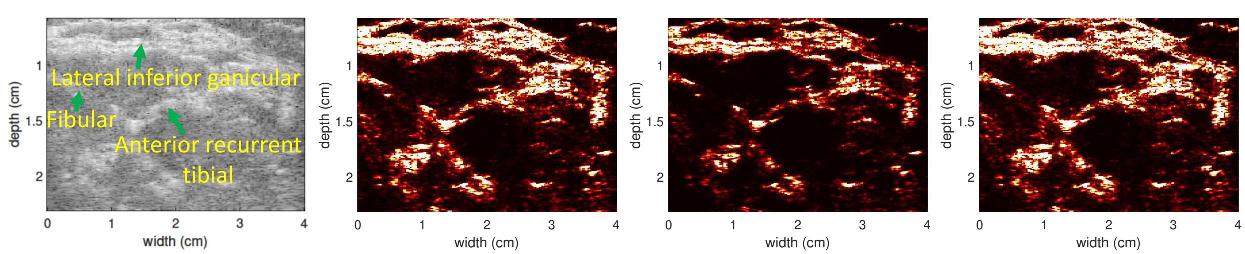
(e) B-mode (f) SVD (g) HOSVD (h) RAPID



(i) B-mode (j) SVD (k) HOSVD (l) RAPID



(m) B-mode (n) SVD (o) HOSVD (p) RAPID



(q) B-mode (r) SVD (s) HOSVD (t) RAPID

(u) Color bar for simulation results (v) Color bar for focused phantom results (w) Color bar for plane-wave phantom results (x) Color bar for *in-vivo* rat results (y) Color bar for *in-vivo* human knee results

Fig. 3: Power Doppler images for simulation, phantom and *in-vivo* data sets. Rows 1-5 correspond to simulation, phantom with focused imaging, phantom with plane wave imaging, *in-vivo* data from a rat's abdomen and *in-vivo* data from the knee of a human subject respectively. Columns 1-4 depict B-mode, power Doppler images obtained from SVD, HOSVD and RAPID respectively. (u), (v), (w), (x) and (y) represent the color bars for power Doppler images obtained from simulation, phantom with focused imaging, phantom with plane wave imaging, *in-vivo* data from a rat's abdomen and *in-vivo* data from the knee of a human subject respectively.

References

[1] M. Kim, C. K. Abbey, J. Hedhli, L. W. Dobrucki, and M. F. Insana, "Expanding acquisition and clutter filter dimensions for improved perfusion sensitivity," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 64, no. 10, pp. 1429–1438, 2017.