Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Comparison of adaptive clutter filters for vector velocity estimation: Realistic simulations and in vivo examples

1st Vincent Perrot
Univ. Lyon, INSA-Lyon, UCBL, UJM-Saint-Etienne
CNRS, Inserm, CREATIS UMR 5220, U1206
Lyon, France
vincent.perrot@creatis.insa-lyon.fr

2nd Jørgen Avdal
CIUS and Dept. of Circulation and Medical Imaging
Norwegian University of Science and Technology (NTNU)
Trondheim, Norway
jorgen.avdal@ntnu.no

3rd Hervé Liebgott
Univ. Lyon, INSA-Lyon, UCBL, UJM-Saint-Etienne
CNRS, Inserm, CREATIS UMR 5220, U1206
Lyon, France
herve.liebgott@creatis.insa-lyon.fr

4th Ingvild Kinn Ekroll
CIUS and Dept. of Circulation and Medical Imaging
Norwegian University of Science and Technology (NTNU)
Kirurgisk klinikk, St. Olavs Hospital
Trondheim, Norway
ingvild.k.ekroll@ntnu.no

***Abstract*—The performance of adaptive FIR filters and SVD filters for vector velocity imaging in the carotid arteries have been investigated. Synthetic data created using a combination of *in vivo* data from a healthy volunteer and flow simulations were used to investigate scenarios with low blood flow, in combination with realistic clutter motion. The results from the synthetic datasets indicate that the investigated FIR and SVD filters performed similarly and shared the same limitations. Although the SVD filter did not show increased performance in terms of bias and standard deviation of the velocity estimates compared to the FIR filter, an advantage of this approach is that adaptive filtering may be performed without prior wall motion estimation.**

***Index Terms*—Adaptive clutter filtering, vector velocity estimation, blood flow imaging**

I. Introduction

For vector velocity imaging of blood flow to be truly quantitative, the velocity estimates should have low variance and bias. Both 2D and 3D velocity estimation techniques have matured in recent years and have a large potential to provide additional diagnostic information in cardiovascular applications. However, accurate blood flow velocity estimation relies on sufficient and accurate suppression of the clutter signal. In particular, for low flow estimation, velocity estimates typically suffer from a negative bias (clutter suppression too weak) or large positive bias accompanied by a large variance (blood suppression too strong). To ensure precise attenuation of the clutter signal throughout the cardiac cycle, the clutter filter should preferably be adapted to the tissue motion. For filters with a well defined frequency response, this would mean varying the stopband and passband cutoff frequencies based on the velocities of the surrounding tissue. However, in regions where blood and tissue velocities overlap in magnitude, these filters can no longer provide accurate blood velocity estimates.

Clutter attenuation based on singular value or eigenvalue decomposition has been proposed to improve detection of low velocity blood flow in several applications, but such filters do not have a well defined frequency response, as is the case for FIR, IIR, and even polynomial regression filters [1]. Due to their nature, it is challenging to predict their performance in different applications both in terms of detection and their impact on e.g. mean velocity estimates.

In this work, the performance of singular value decomposition (SVD) filtering is compared to that of adaptive FIR filtering based on tissue velocities in the context of quantitative vector velocity estimation in the carotid arteries. The challenging scenario of low velocity flow combined with surrounding tissue motion is specifically targeted, and synthetic Doppler data with realistic clutter is used to enable quantification of bias and variance in the resulting velocity estimates.

II. Methods

A. In vivo recordings

Recordings were performed using a GE9L probe connected to a Verasonics Vantage system. Plane wave transmissions (2.5 cycles@4.8 MHz) with alternating insonation angles of $\pm 15°$ were used, resulting in a Doppler PRF of 6 kHz. A multi-angle beamforming scheme was applied on receive [2], enabling robust 2D vector velocity estimation from lag-one autocorrelation velocity estimates.

Two *in vivo* common carotid artery recordings were included in this work: A recording from a healthy volunteer was used in combination with flow simulations to create Doppler signals with known velocity, influenced by realistic clutter. The second recording was used to demonstrate the performance of the filters in a realistic imaging setting. Patient recordings were

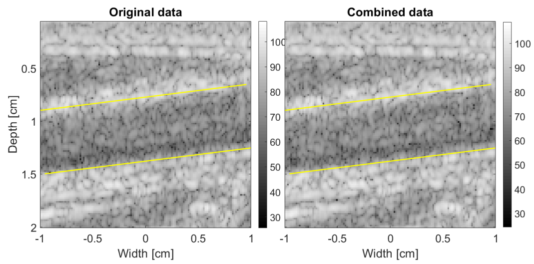

Fig. 1. Images showing a frame from the the original recording (left) and the combined data (right). The combined data consists of the original clutter signal, with the addition of a simulated blood signal originating from the region indicated by the yellow lines.

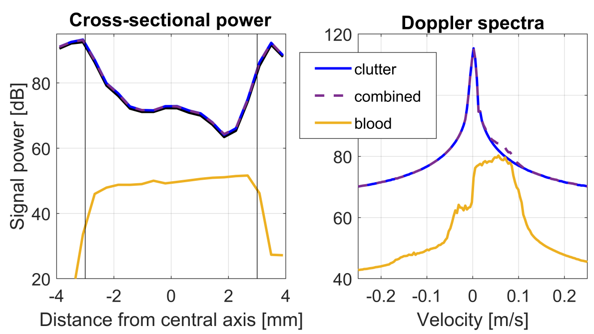

Fig. 2. The left panel shows the average cross sectional signal power in the vessel region for a single frame (broadband clutter scenario), whereas the right panel shows average power spectra of the same signals. The original clutter signal is seen in blue, the simulated blood signal in yellow, and the combined signal in purple.

performed by an experienced clinician, in a study approved by the regional ethical committee.

B. Combining in vivo recordings with flow simulations

Realistic clutter, including reverberations and sidelobes from moving tissue, is challenging to simulate. Therefore, the recording of the healthy volunteer was used to create a synthetic data set consisting of recorded tissue signal and simulated blood signal. Ideally, this provides both realistic clutter, as well as a known flow field. The synthetic data set is produced using 5 steps:

1) Record *in vivo* data
2) Extract vessel geometry from the common carotid artery, modelling the vessel as a straight tube
3) Simulate flow data with the resulting geometry, using the *in vivo* acquisition and beamforming setup
4) Remove original blood signal from *in vivo* data:
   - Low pass filter
   - Add desired amount of noise
5) Add simulated blood flow data to yield the desired clutter-to-blood ratio.

As indicated in Fig. 1, a 3D vessel region with a diameter of 6 mm was simulated using the Field II software [4], using on average 10 scatterers per resolution cell. Stationary flow with a parabolic profile was chosen, with a maximum velocity of 20 cm/s in the middle of the artery. This was done to mimic a challenging part of the cardiac cycle, where the blood velocity in the artery is low, and the tissue motion is at its largest. A relatively large observation window of 45 ms was used (270 samples), to capture the effect of non-stationary clutter.

After lowpass filtering of the *in vivo* recording, the resulting signal was investigated in frequency and eigenvector domains to ensure that no blood signal remained above the noise floor, before adding the simulated blood signal. Two observation windows were investigated in this work, one where the clutter was nearly stationary (narrowband clutter), and one including the maximum tissue motion (broadband clutter).

The original clutter signal, the simulated blood signal and the combined signal is shown in Fig. 2. The figures are obtained using 104 cross-sections normal to the vessel axis, covering the 2 cm long section indicated in Fig. 1.

C. Clutter filtering

Adaptive FIR filtering was performed using a precomputed dictionary of FIR filters to reduce the computational load and computation time. A list of FIR filters was computed using a cutoff from 1 mm/s to 5 cm/s with a discretization step of 0.01 mm/s. Filters are based on an equiripple design with a stopband attenuation of 70 dB and an order of 170, resulting in 100 valid samples in the observation window after filtering. For each frame in the observation window, the filter selected in the dictionary is the one with the closest cutoff to two times the maximum estimated wall velocity in that frame. This factor ensure that no remaining clutter is present without setting a too high cutoff value. Axial wall velocity was estimated based on the complex autocorrelation of the received signal, and a spatial averaging filter with a 2D Hanning kernel of 1 mm was applied to the complex autocorrelation to reduce variance

The adaptive FIR filter was compared to an automatic SVD filtering approach based on spatial correlation, inspired by the work of Baranger et al. [3]. The correlation of spatial eigenvectors from the singular value decomposition of the signal covariance matrix was used to adaptively determine the dimension of the clutter space. Filtering was achieved by removing the corresponding eigenvectors. A third filter was also included, referred to as a weak SVD filter, where thresholding was done based on the power of the eigenvalues of the signal covariance matrix. The power threshold was set at a relatively large value to obtain weak filtering.

D. Velocity estimation

2D vector velocities were estimated based on an extended least squares technique [2] utilizing multiple lag-one autocorrelation estimates.

III. Results

A. Synthetic data set

The left and right panels of Fig. 3 show Doppler velocity spectra from the synthetic data sets with narrowband and broadband clutter respectively. The figures are made by averaging the power spectra from every image point within the vessel region after applying each of the investigated filters. The original clutter signals are shown in black. It can be observed that all three filters adapt to the changing clutter motion, with some differences in attenuation of the lowest velocities.

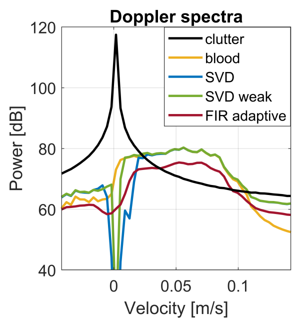

Fig. 3. Doppler velocity spectra in the vessel region of the synthetic data set in the narrowband (left) and broadband (right) clutter scenario.

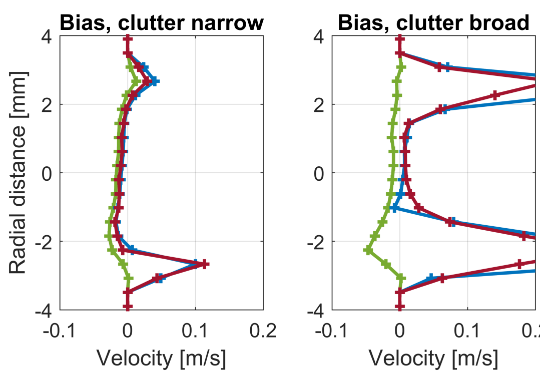

Fig. 4. Bias in estimates of velocity magnitude in an observation window with narrowband clutter (left) and broadband clutter (right).

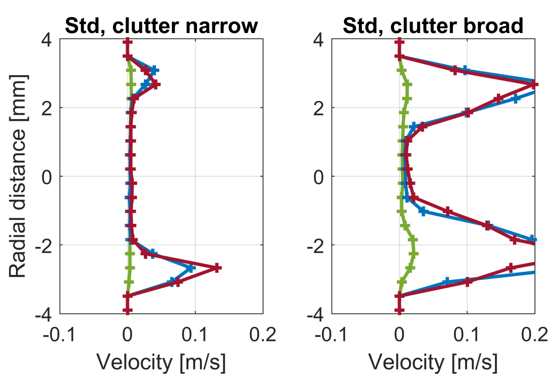

Fig. 5. Standard deviation in estimates of velocity magnitude in an observation window with narrowband clutter (left) and broadband clutter (right).

Figs. 4 and 5 show the bias and standard deviation of the velocity magnitude estimates found using the three investigated filters, for the narrowband and broadband clutter

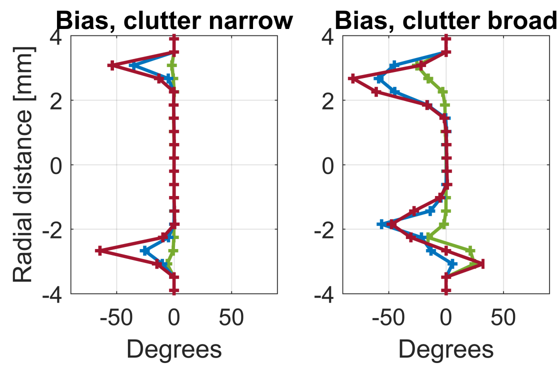

Fig. 6. Bias in estimates of velocity direction in an observation window with narrowband clutter (left) and broadband clutter (right).

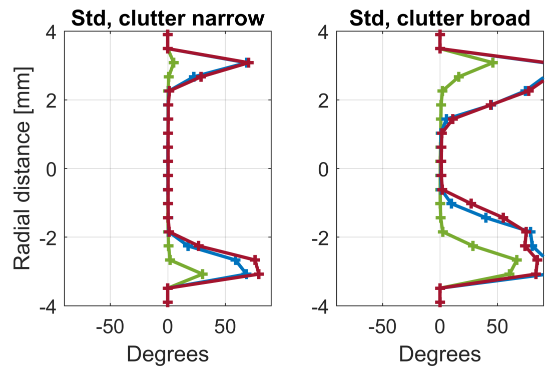

Fig. 7. Standard deviation in estimates of velocity direction in an observation window with narrowband clutter (left) and broadband clutter (right).

scenarios. It is observed that the weak SVD filter in general yields the lowest bias and standard deviation for these low-flow scenarios, whereas the adaptive FIR and spatial correlation based SVD filters yield similar results, with increased bias and standard deviation close to the vessel walls. Figs. 6 and 7 show similar trends for the estimates of the flow direction.

B. *In vivo* example

Figs. 8 and 9 show vector velocity estimates from the common carotid artery of the patient, with the weak SVD filter and the adaptive FIR filter, respectively. The estimates are produced from the same frame, but the resulting field appears more homogeneous when using the adaptive FIR filter. The magnitude and direction of the vector velocity estimates in diastole and systole are shown in Figs. 10 and 11, respectively. Here it may be observed that estimates using the standard SVD filter and adaptive largely are largely in agreement, whereas estimates using the weak SVD filter are lower in magnitude, especially close to the walls.

IV. Discussion

The performance of adaptive FIR filters and SVD filters for vector velocity imaging in the carotid arteries have been investigated. Synthetic data created using a combination of *in vivo* data from a healthy volunteer and flow simulations were used

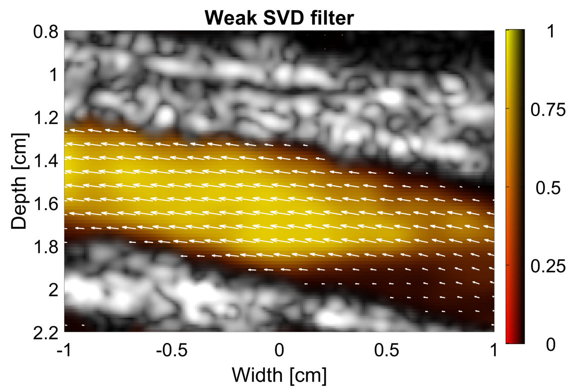

Fig. 8. Vector velocity estimates in the patient common carotid artery using a weak SVD filter.

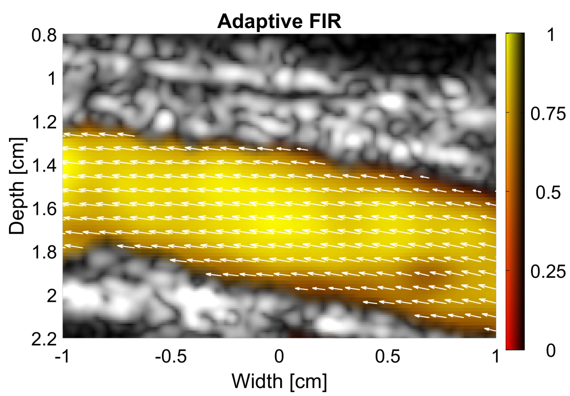

Fig. 9. Vector velocity estimates in the patient common carotid artery using the adaptive FIR filter.

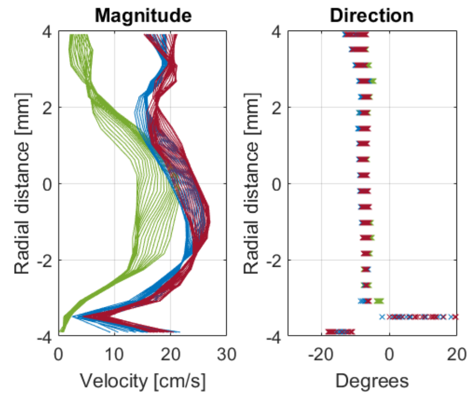

Fig. 10. Cross-section velocity magnitude and directional estimates in diastole.

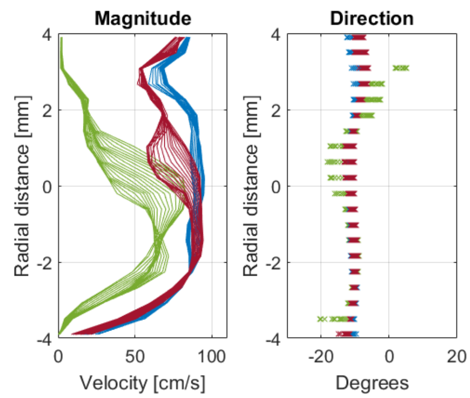

Fig. 11. Cross-section velocity magnitude and directional estimates in systole.

to investigate scenarios with low blood flow, in combination with realistic clutter motion. Additionally, a recording from a patient was used to investigate the performance of the different filters in a realistic imaging scenario – a carotid artery exam of a patient with symptoms of carotid artery disease.

The results from the synthetic datasets indicate that weak filtering, here exemplified with a weak SVD filter, is beneficial in terms of low bias and standard deviation if the blood velocity is low. However, as indicated by the results from the *in vivo* example, residual clutter remains when using this filter, causing underestimation of higher velocities. The low bias and standard deviation seen in the synthetic data set for the weak filter might also be explained by a fair amount of residual clutter near the walls.

The adaptive FIR filter and the SVD filter based on spatial correlation performed similarly in both datasets. Both produced significant bias and standard deviation near the walls in the synthetic data set with broadband clutter, and were able to sufficiently suppress the wall signal in the *in vivo* example. While the SVD filter did not show any improved ability to separate clutter and blood signals, the advantage of this filtering approach is that it may adapt to the wall velocities without the need for wall velocity estimation.

V. Conclusion

For the investigated application, the SVD filter based on spatial correlation and FIR filter based on tissue velocities yielded similar estimates of velocity magnitude and direction. Specifically, the investigated filters shared the same limitations, namely that the velocity magnitude could have a negative bias due to insufficient filtering, or a large variance and bias due to too strong filtering. For the simulated case with low velocity flow comparable to wall velocities, weaker filters that allow some residual clutter were preferable using both filtering techniques. However, *in vivo* recordings showed that this approach yielded negatively biased estimates of high velocity flow.

References

[1] H. Torp, “Clutter Rejection Filters in Color Flow Imaging: A Theoretical Approach,” IEEE TUFFC, vol. 44, pp. 417–424, 1997.
[2] I.K. Ekroll, J. Avdal, A. Swillens, H. Torp, L. Løvstakken, “An extended least squares method for aliasing-resistant vector velocity estimation,“ IEEE TUFFC, vol. 63, pp. 1745–1757, 2016.
[3] J. Baranger, B. Arnal, F. Perren, O. Baud, M. Tanter, C. Demené, “Adaptive spatiotemporal SVD clutter filtering for ultrafast Doppler imaging using similarity of spatial singular vectors“ IEEE Trans. Medical Imaging, vol. 37, pp. 1574–1586, 2018.
[4] J.A. Jensen:, ”Field: A Program for Simulating Ultrasound Systems”, Medical Biological Engineering Computing, pp. 351-353, Volume 34, Supplement 1, Part 1, 1996.