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Vector Doppler imaging of small vessels using directionally filtered Power Doppler images

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***Abstract*—Power Doppler (PD) imaging has become a staple in high frame rate ultrasound imaging due to its ability to image small vessels and slow-moving flows, such as in the case of imaging blood flow in the brain. Alternatively, color Doppler (CD) can be used to determine the one-dimensional directional information of the blood scatterers. This can help determine if the flow is arterial or venous, or distinguish between adjacent flows that have an opposite direction.**

Current methods for estimating 2D blood velocity vectors rely mostly on trigonometric solutions using synthetic apertures or, large plane-wave angles in transmission and sub-apertures in receive to be able to resolve the 2D vector. Relative to PD or CD techniques, these methods are more computationally expensive and have not been successfully used to image blood flow direction within micrometer sized vasculature. In this paper, we propose to use the orientations of the vessels derived from a directional spatial filter in combination with the CD signal to enhance the PD images with directional information. This approach was tested on simulated data as well as on a 2D image containing brain vasculature of a mouse.

***Index Terms*—Power Doppler, Color Doppler, Vector Doppler, Doppler, Gabor filter, Signal Processing**

I. INTRODUCTION

In medical ultrasound, there are multiple imaging techniques that can be used to visualize blood dynamics. For visualization of the mouse brain, high frame-rate power Doppler (PD) imaging has become a well established imaging technique due to its high spatio-temporal resolution which is required to accurately separate the blood motion from the surrounding tissue motion when imaging the small vessels of the mouse brain.

Alternatively, if information on the direction of the flow is required, related techniques such as color Doppler (CD) can be used to help determine if the blood flow is arterial or venous, or help distinguish between adjacent flows that are opposite in direction. Relative to PD imaging, CD imaging has a lower sensitivity, and suffers from signal aliasing which can lead to misleading results [1]. In CD, as the obtained signal is a projection of the flow onto the axis perpendicular to the transducer, it can only discern a direction towards or away from the transducer. As a result, the error in the CD signal scales with the beam-to-flow angle, being high when the flow is perpendicular to the transmitted beam. Unlike with CD, the power of the Doppler signal is not equal to zero even when the flow is perpendicular to the ultrasound beam [2]. This angle dependency of CD imaging also highlights a large advantage of PD techniques.

In this paper, we propose a method to enhance the PD images with directional information. To do this we assume the direction of the flow within the vessels is parallel to the orientation of the vessels, which is possible due to our application of imaging small vessels in the brain. Information on the orientation of the vessels can be extracted using a spatial filter such as a Gabor filter, and can then be combined with the sign of the one-dimensional CD signal to resolve the two-dimensional flow vector.

II. METHODS

A. k-Wave Simulations

The methods for angle extraction were tested using a simulation created using the k-Wave toolbox [3] in MATLAB. To allow for motion to be present in all directions, a rotating ring phantom was created as shown in Fig. 1. To create the simulation phantom, a ring mask was created on a large grid by subtracting two disks of different radii. An image was then created containing the point scatterers (sampled from a standard normal distribution) and was rotated around the center of the ring 1 degree per frame for each successive transmission to simulate the movement along the ring.

TABLE I
K-WAVE SIMULATION PARAMETER SUMMARY

number of elements	206	f0	5.19 MHz
pitch	46.3 μm	Nz/ Nx	216
speed of sound	1540 m/s	dz/dx	46.3 μm

For the simulation, a virtual linear transducer array was defined and placed on top of the simulated medium using the parameters described in Tab. I. Three cycle tone bursts were transmitted to create plane waves that propagate through the

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medium. The plane waves were not angled for this simulation to accurately show the angle dependence of the signal. The obtained RF data was then beamformed using a fast Fourier transform beamformer [4]. This beamformed data forms the basis for the rest of the work.

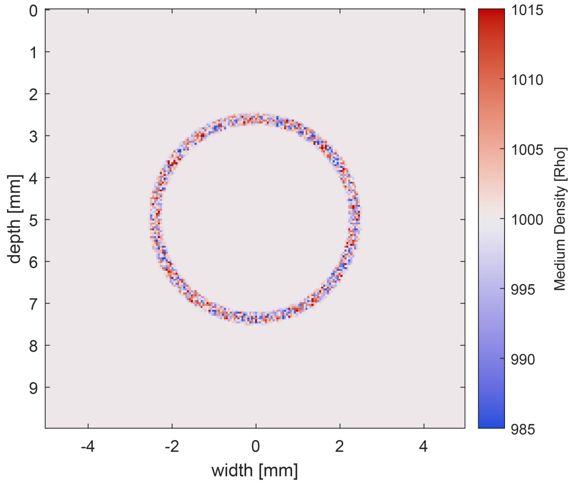

Fig. 1. Simulated rotating ring phantom created in k-Wave with a 2.26 mm inner radius and outer radius of 2.56 mm. The ring was rotated counter-clockwise on a larger grid and downscaled to the original imaging grid to simulate moving point scatterers along the ring at 1 degree per frame

B. Vessel Angle Extraction

The orientation of the vessels within the imaging field of view were extracted using a Gabor filter. This filter is a common imaging processing technique, often used for image feature extraction. While there are many alternative techniques for vessel segmentation [5], the Gabor filter has already been successfully applied to photo-acoustic images [8].

Essentially, this filter analyses the frequency content along a particular orientation of the 2-dimensional image. The even symmetric impulse response of the used Gabor filter was shown by A.K. Jain [9] for orientation 0°, and can be seen in Eq. 1.

$$h(x,y) = exp\{-\frac{1}{2}[\frac{x^2}{\alpha_x^2} + \frac{y^2}{\alpha_y^2}]\}cos(2\pi u_0 x) \tag{1}$$

Here, α_x and α_y denote the spacial constraints along the x and y directions respectively, and u_0 denotes the frequency of the modulating sinusoid along the x-axis. For different orientations, rigid rotations can be applied to the above case.

The Gabor filter was applied to k-Wave simulations detailed in Sec. II-A. To illustrate the effect of the filter, 9 different orientations were spanned between 0° and 180°, and the Gabor filter was applied to the PD images of the rotating phantom. The resulting Gabor magnitude outputs are shown in Fig. 2.

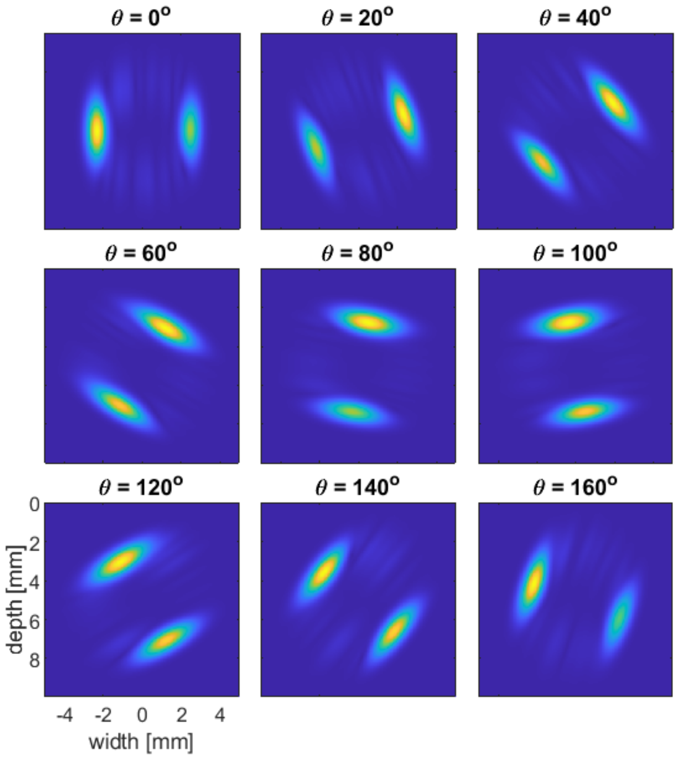

Fig. 2. The resulting Gabor magnitude outputs, displayed for the corresponding input angle when applied to the rotating ring phantom

These images show the regions of the phantom that correspond to the given orientation. Using the Gabor magnitude and the known orientations, the Gabor angles were computed from every point within the simulated vessel and are shown in Fig. 3. This information was next combined with the CD data as demonstrated in the next section.

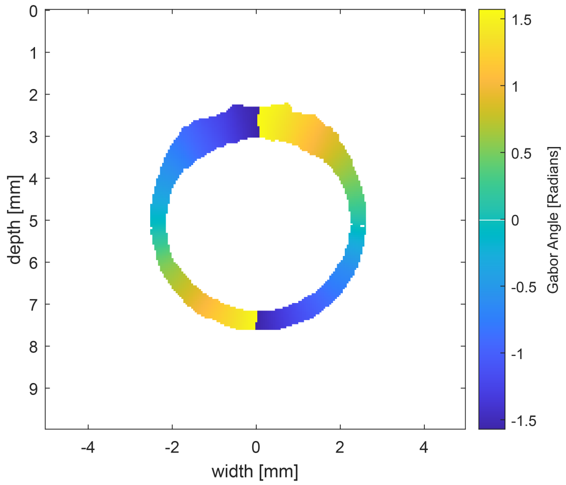

Fig. 3. The spatial angle obtained from the Gabor filter bank when combining the Gabor magnitudes with the corresponding angles

C. Combining vessel orientation with Doppler

The methods for combining the vessel orientation and the sign of the CD signal are illustrated in Fig. 4 for a vessel oriented at 45 degrees. Here, the Gabor angles are used for the orientation of the vessel, and the sign of the CD signal is used to determine if the flow is towards or away from the transducer. The combined information shows the resulting motion direction.

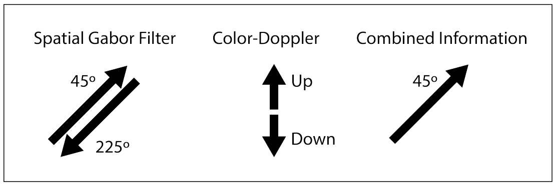

Fig. 4. Illustration of the presented methods for a vessel oriented at a 45 degree angle. The orientation of the vessels are extracted using a Gabor filter. The sign of the color-Doppler signal is then used to resolve the direction of flow within the vessel

D. In Vivo Image Acquisition

In addition to the k-Wave simulations, imaging was also performed on head-fixed C57BL/6 mice through a cranial window. A 128-element high frequency linear array (L35-16v) coupled to a Verasonics Vantage-256 research ultrasound system was used to acquire images of the mouse brain vasculature. The linear array was driven at 31 MHz with a three cycle burst. For this scan, 20 equally spaced angled plane waves were used spanned between $\pm 5°$. The resulting beamformed data [4], with a frame-rate of 600 Hz, was saved in real-time for future post-processing, as well as used for real-time PD imaging. To create PD images, an ensemble of 200 frames was processed using a SVD clutter filter [10].

III. RESULTS

The PD and CD images of the simulation phantom are shown in Fig. 5 (A)-(B). Due to the high sensitivity of the PD images, they were used as a mask to create the CD images in the relevant regions.

The results of combining Gabor orientations with CD images for the ring phantom are shown in Fig. 5 (C). This now contains the direction of motion for every point within the simulation phantom, spanning from 0 to 2π. It can now be combined with the PD signal as magnitude, as shown in Fig. 5 (D) for the complete vector Doppler information.

The resulting PD image, and spatially informed vector Doppler images for a sagittal slice of the mouse brain is shown in Fig. 6 (A) and (B) respectively. For the vector Doppler image, the same image processing steps were performed as previously shown on the k-Wave simulation. The color map shows that as the intensity of the Doppler signal is increased, the represented color intensity is increased, while the given color represents the direction of the flow. For the majority of the large vessels these results were verified by comparing them to previously established anatomical data [11].

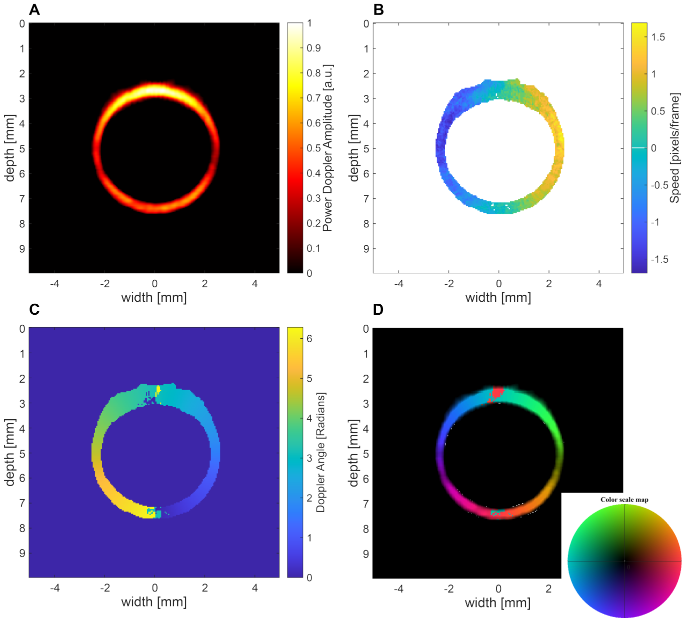

Fig. 5. Combining the vessel orientation with Doppler. **A)** Power Doppler image of the rotating phantom. **B)** The color-Doppler image of the rotating phantom.**C)** The resulting Doppler angle after combining the vessel orientation from the Gabor filter with the 1D motion direction from the color Doppler signal. **D)** The combined spatially informed vector Doppler image, with direction and magnitude spanning over the unit circle.

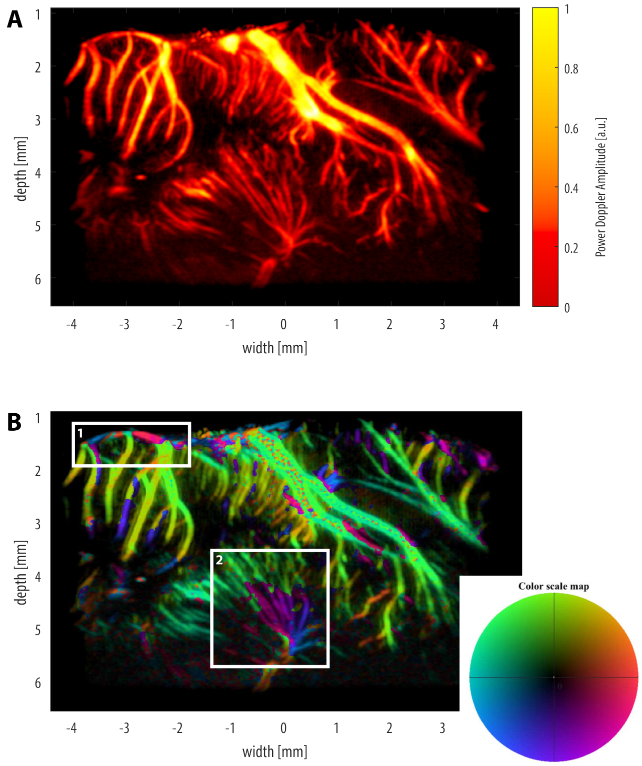

Fig. 6. Spatially informed vector Doppler on the mouse brain. **A)** The Power Doppler image of a sagittal slice of the mouse brain. **B)** The spatially informed vector Doppler image created using the methods presented in this work. Two regions where there is a lack of directional continuity are highlighted in white.

IV. CONCLUSION & DISCUSSION

While the increased sensitivity of PD imaging is invaluable for Doppler imaging of small vessels in the brain, the inherent lack of directional information compared to alternative techniques leaves room for potential investigation. This work demonstrates an approach at using additional information contained in the PD images, namely the orientations of the vessels, to deduce a 2D directional vector Doppler estimate.

Real-time PD imaging remains a computationally heavy processing technique, in part due to the high frame-rate acquisitions that are necessary to be able to distinguish between blood motion and slow moving tissue. Fortunately, the presented method is of low computational complexity, in part because they were applied to the lower frame-rate PD images instead of the high frame-rate raw data. A Gabor filter was chosen to extract the orientation of the vessels within the PD images, as it has already shown to be effective in retinal vessel segmentation [7].

Fig. 5 (A)-(B) shows the PD and CD images for the rotating phantom. The PD signal is highest for the regions closest to the ultrasound transducer due to the higher SNR in these regions, even though the rotation was equal throughout the phantom. For the case of CD imaging, when the flow is almost parallel to the ultrasound transducer the obtained signal is close to zero, even though the power of the Doppler signal is still present. This discrepancy can cause misleading interpretations.

The results from Fig 6 show that the majority of the large vessels follow a similar direction as previously described by anatomical studies [11]. There are a few interesting regions where the presented results are less easy to interpret. In the second highlighted region of Fig. 6 there is a divide in the direction of flow, where the lower regions flow towards the bottom right, and the upper regions flow towards the top left. This lack of continuity can also be seen in the horizontal regions highlighted in region 1. Further research has to be done to investigate the exact cause of this. More complete images of the brain vasculature can be reconstructed by imaging planes adjacent to the current 2D slice. As the implemented methods are also well suited to be scalable to 3D PD data, the 3D data can potentially explain some of these discrepancies if they are caused by out-of-plane motion. Additionally, assuming that the flow in a voxel is related to neighboring voxels, it may be possible to add continuity constrains to the vector Doppler data.

In addition to extracting the vessel orientation, other interesting metrics such as vessel diameters and vessel curvature could also be extracted from the PD images using similar spatial image analysis as those proposed in this paper, and can be used to paint a more complete picture of the vascular connectivity, as shown previously using micro-CT [12]. Such additional information could prove useful, especially when looking at intricate vasculature structures. The PD images shown by Soloukey et. al. [13] obtained when imaging brain tumors in humans during surgery, show that the tumor vasculature may contain interesting structures. It may be possible to distinguish healthy tissue from tumorous tissue if the vessel structures can be properly parameterized.

We hope that due to the relatively low computational burden of the presented work on the already existing PD imaging pipeline, that our methods can provide helpful additional information on the direction of flow within the vessels and forms a basis for future work into quantitative Doppler imaging.

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