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A Preliminary Study to Extend Nyquist Flow Speed of Echocardiography using a Dual-PRF Dealiasing Method

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1. Introduction

Blood flow measurement in the heart is one of the most important diagnostic indicators in evaluating cardiac function. To assess and quantify the blood flow measurement, color Doppler ultrasound imaging is an essential imaging modality. While conventional color Doppler imaging is real-time and noninvasive, it is limited to measuring only a component of the blood flow velocity component along the ultrasound beam. Our research group has reported an imaging framework[1)] that estimates 2D velocities based on trigonometric relationships between two 1D velocities obtained by transmitting diverging waves in two different directions. Nevertheless, one problem with this method was that, as the number of transmission directions increases, the pulse repetition frequency (PRF) in the same direction becomes smaller, resulting in reduced robustness against aliasing artifacts. To achieve more robust 2D flow vector estimation, this study aimed to propose a method to extend the Nyquist speed using two PRFs, leveraging the staggered multiple-PRF ultrafast color Doppler[2)] and investigate the optimal imaging scheme for echocardiography. On this topic, this paper specifically presents the preliminary trials to test the new framework using a straight constant flow model and to compare the performance of the proposed method with that of conventional "single-PRF" color Doppler method.

2. Method

2.1 Dual-PRF dealiasing method

The Nyquist velocity V_N in the color Doppler method is given by

$$V_N = \frac{PRF \times \lambda}{4} \qquad (1),$$

where λ is the wavelength of the acoustic pluses. In the dual-PRF method, two different PRFs (PRF_1 and PRF_2)were first selected. PRF_1 was defined based on the imaging depth and the expected maximum flow velocity, and the other PRF was set in the following relationship.

$$PRF_2 = \frac{p}{q} PRF_1 \qquad (2),$$

where p and q are mutually prime natural numbers and $p < q$. Also, the relationship between the Nyquist speeds V_{N_1} and V_{N_2} can be written as,

$$V_{N_2} = \frac{p}{q} V_{N_1} \qquad (3).$$

To illustrate the principle of the Nyquist velocity being extended, **Fig.1** depicts the relationship between actual and measured velocities when $p = 2$ and $q = 3$. As shown Fig.1, each color-coded region has a unique difference between flow speed value measured by PRF_1 and PRF_2, respectively. This difference can be used to extend the Nyquist speed up to twice the V_{N_1}.

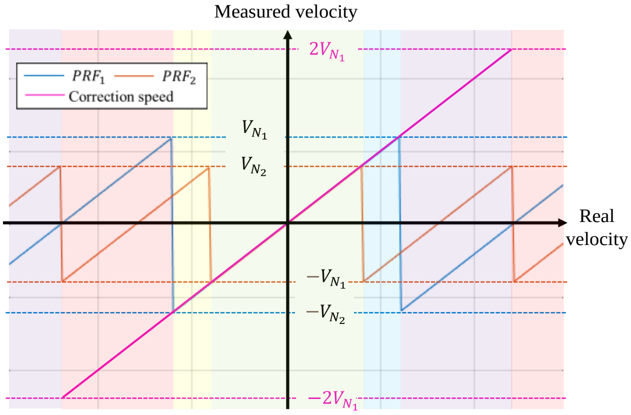

Fig.1 Relationship between speeds at two PRFs.

Each unique region in Fig.1 can be identified by calculating,

$$\mathrm{nint}\left(q\frac{V_{D_2} - V_{D_1}}{2V_{N_1}}\right) \qquad (4),$$

here nint is the function to calculate the closest integer value.

Based on the integer number acquired in eq. (4), the speed correction in the dual-PRF dealiasing method was performed. The combination of Nyquist numbers n_{N_i} was derived from the integer number and **Table I.** The derived Nyquist number n_{N_i} are substituted into the following equation to finally calculate the dealiased Doppler velocity V_D^u,

$$V_D^u = \frac{\left(V_{D_1} + 2n_{N_1}V_{N_1}\right) + \frac{q}{p}\left(V_{D_2} + 2n_{N_2}V_{N_2}\right)}{1 + \frac{q}{p}} \qquad (5).$$

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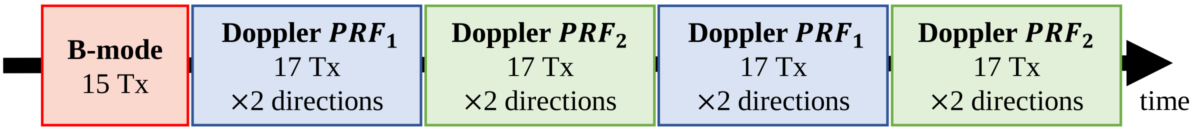

Fig.2 Transmission sequence for acquiring one frame.

Table I Relationships between the integer number given in eq. (4) and the number of aliasing wrapping for Doppler measurement at each PRF.

nint $\left(q_2 \frac{V_{D_2}-V_{D_1}}{2V_{N_1}}\right)$	n_{N_1}	n_{N_2}
2	0	-1
1	1	1
0	0	0
-1	-1	-1
-2	0	1

2.2 Experimental Setup

Phantom experiments were performed to evaluate the performance of the dual-PRF dealiasing method on a sector probe imaging setting. A research-purpose ultrasound system (Vantage 256 system, Verasonics) equipped with a sector probe (64 channels, fc: 2.5 MHz) was used to image a Doppler 403 flow phantom with a flow tract of 5 mm in diameter and tilted at 40°. The flow rate was set as constant at 8.0 ml/s.

A transmission sequence to generate a pair of a B-mode image and a flow vector map was configured as shown in **Fig.2**. First, B-mode images frame was acquired by emitting 15 diverging were pulses (Tx angles range: ±42°). Subsequently, the dual-PRF Doppler measurement sequence consisted of four blocks shown in Fig.2 was run. Each block emitted 34 diverging waves from ±30° alternatively. PRF_1 was set for the first and third blocks, while PRF_2 was used for the rest of blocks. In each experiment, 10 frames of data were acquired. The echo data of Doppler measurement at each PRF was processed with the SVD clutter filtering and lag-1 autocorrelator to estimate V_{D_1} and V_{D_2} that can be used to estimate an aliasing-free velocity map. Later, the estimated velocity maps were averaged over 9 frames. For comparison, the conventional single-PRF color Doppler imaging was performed with data taken at PRF_1 only and the aliasing artifacts were removed by the phase unwrapping.

3. Results and Discussion

Color Doppler images for the Tx angle of +30° respectively derived from the dual-PRF dealiasing method and single-PRF are shown in **Fig.3**. The absolute error of the two dealiased color Doppler images is shown in Fig.3 (c), and the mean absolute error (MAE) was 25.9 mm/s. Up to the depth of 65 mm, the dual-PRF dealiasing method was observed to show the same results as the single-PRF method, but for the deeper region (> 65 mm), the error was found to be larger. This might be due to the missing color Doppler data of PRF_2 at deeper than 65 mm depth, which can be seen in Fig.3 (d). This finding suggested that, when using the dual-PRF dealiasing method, color Doppler images of both PRFs need to be highly accuracy. In the future study, the devised framework will be further evaluated under other flow conditions such as pulsating flow.

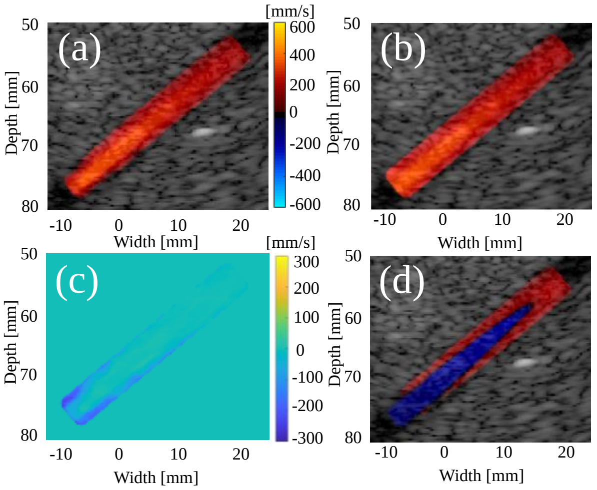

Fig.3 Color Doppler images with (a) dual-PRF dealiasing method, and (b) single-PRF, (c) absolute error of (a) and (b), (d) color Doppler of PRF_2 used in dual-PRF dealiasing method.

3. Conclusion

In this study, the performance of the dual-PRF dealiasng method for a sector probe imaging was evaluated by a straight tube phantom experiment. The results showed that if the color Doppler of each PRF used in the dual-PRF dealiasing method was accurately acquired, the performance was as good as that of color Doppler using the single-PRF method.

References

1. M. Maeda *et al.*: Jpn. J. Appl. Phys. **57** (2018) 07LF02-1.
2. D.Posada *et al.*: IEEE Trans. Med. Imaging **35** (2016) 1510.