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Blood flow imaging using singular value decomposition filter during high-intensity focused ultrasound exposure

強力集束超音波照射中における特異値分解フィルタを用いた血流イメージング

Hayato Ikeda[1‡], Shin Yoshizawa[2], Moe Maeda[1], Shin-ichiro Umemura[1], and Yoshihumi Saijo[1] ([1]Grad. School of Biomed. Eng. Tohoku Univ.; [2]Grad. School of Eng. Tohoku Univ.)
池田隼人 [1‡], 吉澤晋 [2], 前田萌 [1], 梅村晋一郎 [1], 西條芳文 [1]([1] 東北大院　医工, [2] 東北大院　工)

1. Introduction

High-Intensity Focused Ultrasound (HIFU) is a minimally invasive treatment modality to induce thermal coagulation.[1)] In a clinical case of a twin reversed arterial perfusion (TRAP) sequence, noninvasive blood flow occlusion in an acardiac fetus was successfully achieved by HIFU treatment externally applied to the maternal abdomen.[2)] The occlusion of vessels was monitored by conventional Doppler imaging during the intermission time of HIFU in the session, which suggested the need of real-time and noninvasive monitoring during HIFU exposure to enhance the safety and accuracy of the treatment. It has already demonstrated that the crosstalk from HIFU to the imaging signal can be reduced by subtracting the RF signal without imaging pulse (Passive imaging) from the RF signal with imaging pulse (Active imaging).[3)]

In this study, we propose a novel filtering method to monitor blood flow during HIFU exposure by combining a singular value decomposition (SVD)[4)] with the above-described HIFU noise reduction method.

2. Materials and Methods

2.1 Experimental setup

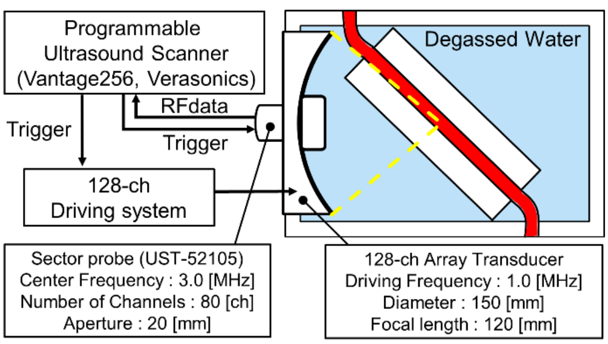

Fig. 1 Schematic of experimental setup

Fig. 1 shows a schematic of the experimental setup. HIFU was generated from a 128-ch 2D-array transducer (diameter: 150 mm and focal length: 120 mm) at a driving frequency of 1.0 MHz by using a 128-ch driving system. A sector probe with a center frequency of 3.0 MHz (Hitachi Aloka Medical, UST-52105) was connected to a programmable ultrasound scanner (Vantage256, Verasonics) to acquire RF data for ultrasonic imaging. A blood flow phantom (Poly-Vinyl Alcohol) with a 4 mm diameter cylindrical cavity was used as the object for HIFU exposure. The phantom containing cellulose as ultrasonic scatterers was set at the HIFU geometric focus. The direction of the cylindrical cavity was set at a 45° angle to the probe surface and a blood-mimicking fluid (ATS Laboratories, Doppler test fluid model 707) was flown through it at a steady flow velocity of 20 cm/s.

2.2 HIFU exposure and RF data acquisition

Fig. 2(a) shows the sequence of HIFU exposure and RF signal acquisition. The intensity and exposure duration of HIFU were 2 kW/cm^2 and 50 ms, respectively. RF signals of 24 frames were acquired sequentially at a rate of 500 Hz during the HIFU exposure. **Fig. 2(b)** shows the sequence of the imaging. Diverging waves were transmitted for high-speed ultrasonic images. A set of passive and active imaging was performed 5 times with diverging waves steered at different angles of -5, -2.5, 0, 2.5, 5° at a repetition period of 200 μs for compounding operation to construct a frame of image.

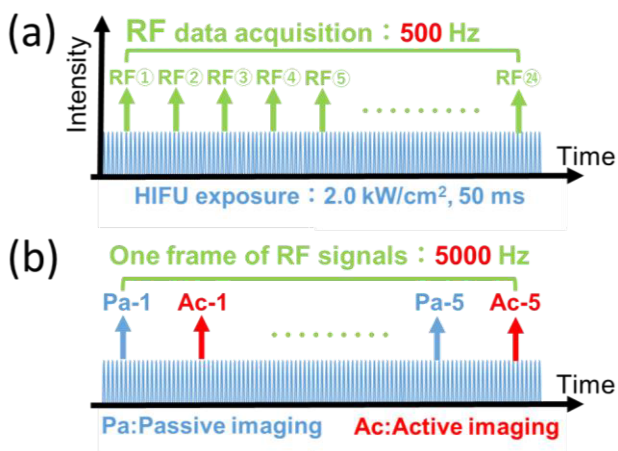

Fig. 2 Sequence of (a) HIFU and imaging, (b) RF data to construct a frame of image.

2.3 HIFU noise reduction and SVD filtering.

A certain time after the start of HIFU exposure, the response of the imaging hardware to the HIFU exposure should reach the steady state with a repetition period inversely proportional to the fundamental HIFU frequency. Therefore, the imaging pulse responses during HIFU exposure could be estimated by subtracting the RF signals of passive imaging from the RF signals of active imaging. After that, the imaging pulse responses of 24 frames were decomposed into a spatial matrix $\mathbf{U}$, a singular values matrix Δ, and a temporal matrix $\mathbf{V}$ as

$$\mathbf{S}_{\mathbf{Image}}(z,x,t) = \mathbf{U}\cdot\Delta\cdot\mathbf{V}^* = \sum_{i=1}^{24} \boldsymbol{\lambda}_i \cdot \mathbf{U}_i(z,x)\cdot\mathbf{V}_\mathbf{i}(t) \qquad (1)$$

The components were arranged from the most energetic to the least ($\boldsymbol{\lambda}_1 \rightarrow \boldsymbol{\lambda}_{24}$). By choosing the singular value number, the blood flow signals were identified.[5)]

3. Result and Discussion

Fig. 3 shows a set of spatiotemporal couples vectors of $\mathbf{U}$(spatial matrix) and $\mathbf{V}$(temporal matrix) after employing the HIFU noise reduction method and the SVD filtering. HIFU propagated from up to down in these images. The tissue signals observed in $\mathbf{U_1}$ and $\mathbf{V_1}$ were constant. The blood flow signals were observed in $\mathbf{U_{10}}$ and $\mathbf{V_{10}}$. The remained HIFU noise signals were observed between the tissue and blood flow signals.

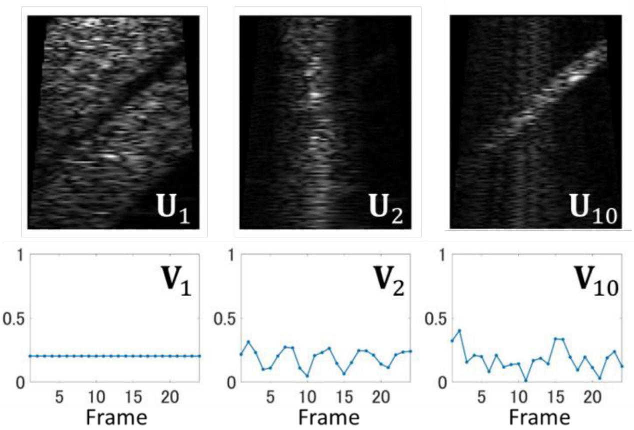

Fig. 3 Set of spatiotemporal couples of $\mathbf{U}$ and $\mathbf{V}$.

Fig. 4 shows a set of B-mode image and power integral of blood flow image after SVD filtering (a) before HIFU exposure, (b) during HIFU exposure, and (c) during HIFU exposure with HIFU noise reduction method. The results demonstrate that the combining of the HIFU noise reduction method and the SVD filter is useful for monitoring the blood flow during HIFU exposure.

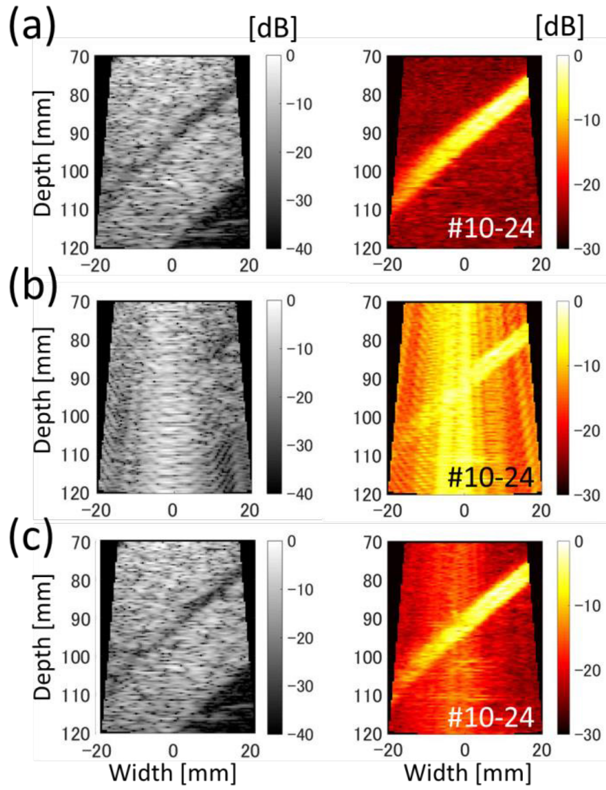

Fig. 4 Set of B-mode image and power integral of blood flow image after SVD filtering (a) before HIFU exposure, (b) during HIFU exposure, and (c) during HIFU exposure with HIFU noise reduction method.

4. Conclusion

In this study, we propose a novel filtering method for monitoring blood flow during HIFU exposure by combining an SVD filter with the HIFU noise reduction method. The HIFU noise was reducted by subtracting the RF signals of passive imaging from the RF signals of active imaging while keeping the tissue and blood flow signals intact. After that, the blood flow signals were identified by employing the SVD filter, on the basis of the spatiotemporal characteristics and amplitudes of these signals.

References

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hayato.ikeda.t7@dc.tohoku.ac.jp