Blood Flow Velocity Vector Imaging with High Frame Rate Imaging Methods

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Abstract – **Conventional blood flow imaging is an important medical diagnostic tool. In this paper, the same processing technique is applied to the high frame rate (HFR) imaging method developed previously to obtain two-dimensional (2D) (in principle, the method is also applicable to three-dimensional (3D)) blood flow velocity vector images. This takes advantage of the HFR imaging method where multiple 2D or 3D images, instead of a single line, can be reconstructed from a single transmission with multiple reception beams steered at different angles.**

To show the feasibility of the method, an *in vivo* experiment of an artery of the right arm of a volunteer was performed with a home-made HFR imaging system. In the experiment, a broadband linear array transducer of 128 elements, 5-MHz center frequency, 38.4-mm aperture, 5-mm elevation width, and 20-mm elevation focal distance was used. The transducer was excited with a one-cycle sine wave centered at the frequency of the transducer to produce pulsed plane waves at a repetition period of 80 microseconds. Echo signals were digitized at 40-MHz and 12-bit resolution. A set of two 2D radio-frequency (RF) (before the envelope detection) images steered at 0 (perpendicular to the transducer surface) and 15 degrees in reception, respectively, was reconstructed from each transmission. Blood flow velocity component images were reconstructed simultaneously from these images with the conventional color flow processing techniques using 16 transmissions. Combining the velocity component images, velocity vector images at a frame rate of 12,000 frames/s can be obtained.

Keywords – Blood flow imaging; velocity vector imaging; high frame rate; HFR; limited diffraction beams; medical imaging; beamforming

I. INTRODUCTION

Based on the limited-diffraction beam theory [1]-[4], a method for high frame rate (HFR) (3750 frames or volumes per second for a depth of about 200 mm in biological soft tissues) two-dimensional (2D) or three-dimensional (3D) imaging was developed in 1997 [5]-[9]. In this method, one or more images can be reconstructed from a single transmission, producing a high image frame rate that is the same as the transmission pulse repetition rate. Recently, the HFR imaging method was extended [10]-[15] to include multiple transmissions using either limited-diffraction array beams [16]-[18] or steered plane waves [5], [19], [20] to increase image field of view and improve image quality, which is equivalent to performing a dynamic focusing in both transmission and reception of a conventional delay-and-sum (D&S) method [21]. Furthermore, a square-wave aperture weighting method has been developed to allow only one or two transmitters to drive all transducer elements to simplify the transmitter subsystem of an imager without compromising image quality [10]. The square-wave aperture weighting method has also been applied to the reception beamforming to replace some high-speed digital circuits to further simplify imaging systems. In addition, the method can be used to develop a general-purpose realtime spatial spectrum analyzer for waves impinging on the surface of an array transducer [22], which is similar to the Fourier optics [23] but contains more information because both the phase and amplitude of the waves are naturally acquired.

Taking advantage of the HFR imaging methods, in this paper, a method for HFR velocity vector imaging is developed [24]. In this method, a set of two or more 2D or 3D images steered at different angles in reception is reconstructed from a single transmission beam. Repeating the transmission beam in the same direction multiple times, say, 16, velocity vector images at a very high frame rate can be reconstructed with the conventional color flow imaging method [25]. To maintain a large field of view for the HFR velocity vector images, alternative methods such as a combination of the conventional color flow imaging [25] to obtain axial, and other method to obtain transverse, flow velocities developed in 1996 [17] and 1998 [26] could be used. Interpolations to obtain new radio frequency (RF) image lines at different angles may contain motion information from different angles and thus could also be used for velocity vector imaging.

An *in vivo* experiment was carried out for the blood flow velocity vector imaging on an artery of the right arm of a human volunteer with a home-made general-purpose HFR imaging system [10], [27], [28]. In the experiment, a broadband linear array transducer of 128 elements, 5-MHz center frequency, 38.4-mm aperture, 5-mm elevation width, and 20-mm elevation focal distance was used to produce a plane wave repeatedly firing in the same direction. A 5-MHz one-cycle sine wave pulse was used in the transmissions with a pulse repetition period of 80 microseconds. A set of two 2D RF (before the envelope detection) images steered at 0 (perpendicular to the transducer surface) and 15 degrees in reception, respectively, was reconstructed from each transmission using RF echo signals digitized at 40 MHz and 12-bit resolution. Blood flow velocity component images were reconstructed simultaneously with the conventional color flow processing techniques [25]. From the velocity component images, each of which was obtained with 16 transmissions to reduce noise, velocity vector images were reconstructed at a frame rate of 12,500 frames/s by sliding one frame at a time.

It is worth noting that since more than one 2D or 3D image can be reconstructed from a single transmission, the quality of

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B-mode image could be improved with a coherent superposition to increase resolution or an incoherent superposition to reduce speckles without reducing image frame rate, while producing flow velocity vector images at the same time.

II. METHOD

To obtain HFR velocity vector images, HFR RF B-mode images need to be reconstructed first. A program that is based on the HFR image reconstruction method developed in 1996 was used for the image reconstructions [5], [6]. The theory of the HFR imaging and its extension are the basis for understanding the method and can be founded in [5] and [10].

To demonstrate the method of velocity vector imaging, an *in vivo* experiment was performed. In the experiment, a 5-MHz broadband linear array transducer of 128 elements and 38.4-mm aperture was used. A home-made general-purpose HFR imaging system [10], [27], [28] was used to acquire echo signals of an artery near the elbow section of a healthy volunteer. The imaging system has 128 independent wideband (0.05-10 MHz) linear power amplifiers (their output is capable of driving a 75-ohm resistive load at up to +/-144V peak) and 128 independent broadband (0.25-10 MHz) time-gain-control (TGC) receivers. RF echo data acquired were digitized at 40-MHz sampling rate and 12-bit resolution. The data were then transferred to a personal computer (PC) via a standard USB 2.0 port for image reconstructions. A short pulse (one-cycle sine wave) at a center frequency of the transducer was used to excite the transducer and echoes were received at the full bandwidth of the receiver (about 10 MHz) to maintain a high axial resolution of the velocity vector images. However, this has produced high noise and a wider spectral width of Doppler signals that may reduce the accuracy of velocity estimation. To improve the quality of velocity vector images, transmissions of a narrower bandwidth tone burst of a few cycles and a matched receiver bandwidth may be needed at the expense of the axial resolution.

With images reconstructed for receive beams steered at different angles from each transmission, velocity vector component images can be reconstructed by transmitting multiple times in one direction. The conventional color flow imaging method [25] was used to estimate the velocity components, except that the mean frequency shift was obtained via fast Fourier transform that was applied to the complex echo samples derived from multiple consecutive frames of images. A one-tap finite impulse response (FIR) filter was used to reduce the effects of slow motions of the tissues. In principle, at least two transmissions are required to obtain the velocity information with the color flow imaging method. To reduce noise, we used 16 transmissions in one direction. Combining the velocity component images, velocity vector images of a frame rate as high as the repetition rate of the transmission pulses can be reconstructed by sliding the signal processing window one frame at a time.

In addition to the flow velocity imaging, the multiple images reconstructed from different receiving angles could be used to increase the resolution of B-mode images by a coherent superposition or to reduce speckle noise with an incoherent superposition, without reducing image frame rate.

III. RESULTS

Reconstructed images of the artery are shown in Figs. 1 and 2, for receive beams steered at 0 and 15 degree angles relative to the vertical direction, respectively. The straight lines near the top of the images are produced by the ringing of the transmission beams. The boundary between the water (the large dark area on the top) and the skin can be clearly seen due to a wide bandwidth of the system. A large artery marked with a rectangular box can also be seen in the tissue.

Velocity component images that correspond to the box areas of Figs. 1 and 2 are shown in Figs. 3 and 4, respectively. Due to the trade-off between image resolution and noise as explained earlier, the velocity component images have been contaminated by the noise and thus are not smooth.

From Figs. 1 and 2, it is clear that images reconstructed from different steering angles in receive have different speckle patterns and thus can be used to reduce speckle noise without lowering image frame rate.

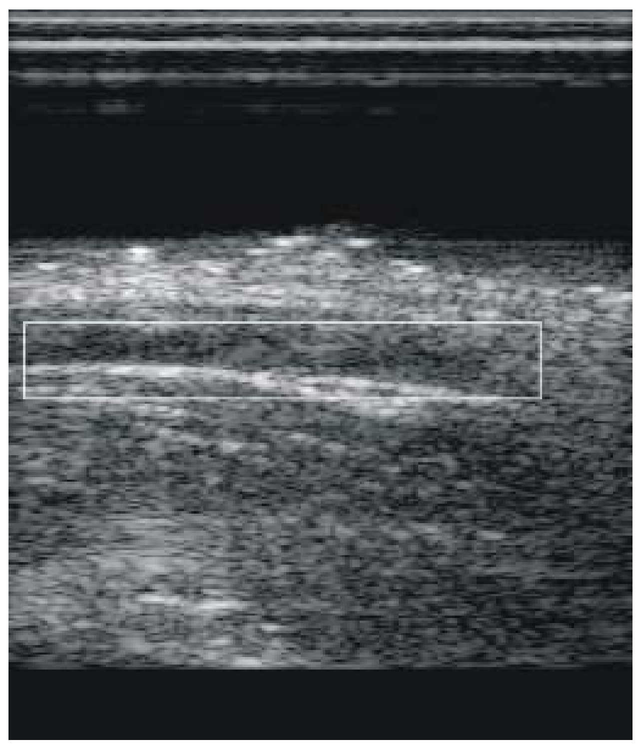

Figure 1. Reconstructed B-mode image of an artery of the right arm of a volunteer used for HFR velocity vector imaging with the HFR imaging method [5]-[9]. A 5-MHz broadband transducer (38.4-mm aperture, 5-mm elevation aperture, and 20-mm elevation focal distance) was used (the transducer was at the top of the image). A broadband plane wave that was perpendicular to the transducer surface was used in transmission. In the image reconstruction, the receive beam was not steered. A plastic bag sealed with distilled water was placed between the transducer surface and the skin of the arm to avoid multiple reflections from bones and allow the

object (artery) to be located around the elevation focal distance. The image was acquired at a frame rate of 12,500 per second (80-μs period) for about 1 second duration. It is log-compressed with a 50-dB dynamic range. The dimension of the image is 38.4 mm in width and 45 mm in height (256×300 pixels). A box of 30.6 mm by 4.5 mm (204×30 pixels) indicates the area where the blood flow velocity image was reconstructed.

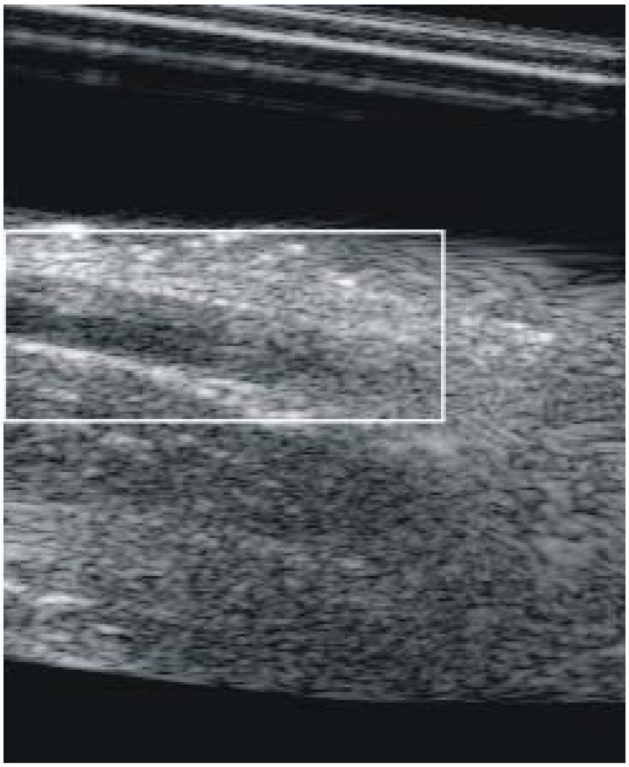

Figure 2. This figure is obtained under the same experiment conditions as those in Fig. 1, except that in the image reconstruction, the receive beam was steered at an angle of 15 degrees relative to the transducer axis. The image size is 37.05 mm by 45 mm (247×300 pixels), which is slightly smaller than that of Fig. 1 due to the receive beam steering. The box shows an area (25.2 mm by 10.7 mm or 168×71 pixels) where the velocity image was reconstructed. The image was produced with the same single broadand plane wave transmission as that in Fig. 1.

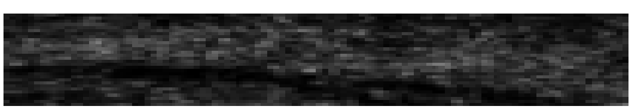

Figure 3. Magnitude of the velocity component image reconstructed with the conventional color flow processing technique [25] without receive beam steering. The imaging area corresponds to the box area of Fig. 1. In the image reconstruction, 16 transmissions were used to obtain both in-phase and quadrature components of the Doppler signal. Sliding one transmission at a time, a frame rate of 12,500 can be achieved for a velocity component image. A one-tap finite impulse response (FIR) wall filter was used to reject slow tissue motions. The image size is 30.6 mm by 4.5 mm (204×30 pixels). It is displayed in a linear scale. The image is noisy because the same conditions that were used to obtain the B-mode images in Figs. 1 and 2 were used (a broadband one-cycle sine wave instead of typical 4-5 cycle tone bursts was used). In addition, the imaging system has a wide receive bandwidth (0.25-10 MHz) that allows more noise to enter the receivers. Despite the noise problem, signals from the vessel walls are rejected well.

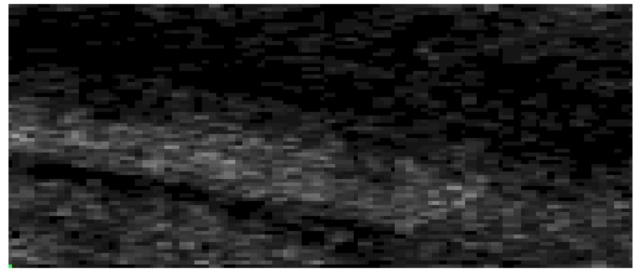

Figure 4. Magnitude of the velocity component image reconstructed with the conventional color flow processing technique [25] with 15 degree receive beam steering. The imaging area corresponds to the box area of Fig. 2. Other conditions for the image reconstruction are the same as those in Fig. 3. The image size is 25.2 mm by 10.7 mm (168×71 pixels). Combining the image in Fig. 3, a high frame rate velocity vectore image can be reconstructed (using both the in-phase and quadrature components to determine the direction of the flow).

IV. Conclusion

A high frame rate (HFR) velocity vector imaging method has been developed based on the previous studies of limited-diffraction beams [1]-[4] and the HFR imaging methods [5]-[10]. This method can achieve a high image frame rate because multiple RF images can be reconstructed from a single transmission in the HFR imaging method with receive beam steering (or with other methods as mentioned in the Introduction).

An *in vivo* experiment was carried out to study the feasibility of the method. Results show that multiple images at different steering angles of receive beams can be reconstructed from a single transmission. These images can then be used to obtain velocity vector component images from multiple transmissions in the same direction using the same processing technique as in the conventional color flow imaging [25].

In this preliminary study, although the velocity component images can be reconstructed, they are noisy due to the wide bandwidth used. In the future, a narrower bandwidth will be used in both transmission and reception by transmitting tone bursts of more cycles (not just one cycle) and using a narrower receive bandwidth to reduce noise and improve the accuracy of the velocity estimation.

In addition to obtaining the velocity vector images, the multiple images reconstructed with the high frame rate imaging method could be used to improve image resolution and to reduce sidelobe or speckle noise.

Acknowledgments

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References

[1] Jian-yu Lu and J. F. Greenleaf, "Nondiffracting X waves --- exact solutions to free-space scalar wave equation and their finite aperture realizations," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 39, no. 1, pp. 19-31, January 1992.

[2] Jian-yu Lu and J. F. Greenleaf, "Experimental verification of nondiffracting X waves," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 39, no. 3, pp. 441-446, May 1992.

[3] Jian-yu Lu and Anjun Liu, "An X wave transform," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 47, no. 6, pp. 1472-1481, November 2000.

[4] Charles Day, "Intense X-shaped pulses of light propagate without spreading in water and other dispersive media," *Physics Today*, vol. 57, no. 10, pp. 25-26, October 2004.

[5] Jian-yu Lu, "2D and 3D high frame rate imaging with limited diffraction beams," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 44, no. 4, pp. 839-856, July 1997.

[6] Jian-yu Lu, "Experimental study of high frame rate imaging with limited diffraction beams," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 45, no. 1, pp. 84-97, January 1998.

[7] Jian-yu Lu, "Transmit-receive dynamic focusing with limited diffraction beams," in *1997 IEEE Ultrasonics Symposium Proceedings*, 97CH36118, vol. 2, pp. 1543-1546, 1997 (ISSN: 1051-0117).

[8] Hu Peng and Jian-yu Lu, "High frame rate 2D and 3D imaging with a curved or cylindrical array," in *2002 IEEE Ultrasonics Symposium Proceedings,* 02CH37388, vol. 2, pp. 1725-1728, 2002 (ISSN: 1051-0117).

[9] Glen Wade, "Human uses of ultrasound: ancient and modern," *Ultrasonics*, vol. 38, pp. 1-5, 2000.

[10] Jian-yu Lu, Jiqi Cheng, and Jing Wang, "High frame rate imaging system for limited diffraction array beam imaging with square-wave aperture weightings," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 53, no. 10, pp. 1796-1812, October 2006.

[11] Jian-yu Lu and Jiqi Cheng, "System for extended high frame rate imaging with limited diffraction beams," *United States Patent* (filed).

[12] Jiqi Cheng and Jian-yu Lu, "Fourier based imaging method with steered plane waves and limited-diffraction array beams," in *2005 IEEE Ultrasonics Symposium Proceedings*, 05CH37716C, vol. 2, pp. 1976-1979, 2005 (ISSN: 1051-0117).

[13] Jiqi Cheng and Jian-yu Lu, "Extended high frame rate imaging method with limited diffraction beams," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 53, no. 5, pp. 880-899, May 2006.

[14] Jing Wang and Jian-yu Lu, "Effects of phase aberration and noise on extended high frame rate imaging," *Ultrasound in Medicine and Biology* (submitted).

[15] Jing Wang and Jian-yu Lu, "Motion artifacts of extended high frame rate imaging," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* (submitted).

[16] Jian-yu Lu, "Limited diffraction array beams," *International Journal of Imaging System and Technology*, vol. 8, no. 1, pp. 126-136, January 1997 (ISSN: 0899-9457).

[17] Jian-yu Lu, "Improving accuracy of transverse velocity measurement with a new limited diffraction beam," in *1996 IEEE Ultrasonics Symposium Proceedings*, 96CH35993, vol. 2, pp. 1255-1260, 1996 (ISSN: 1051-0117).

[18] Jian-yu Lu and Jiqi Cheng, "Field computation for two-dimensional array transducers with limited diffraction array beams," *Ultrasonic Imaging*, vol. 27, no. 4, pp. 237-255, October 2005.

[19] Jian-yu Lu and Shiping He, "Increasing field of view of high frame rate ultrasonic imaging," *Journal of Acoustical Society of America*, vol. 107, no. 5, pt. 2, pp. 2779, May 2000 (abstract).

[20] Jian-yu Lu, "Nonlinear processing for high frame rate imaging," *Journal of Ultrasound in Medicine*, vol. 18, no. 3 (Supplement), p. S50, March, 1999 (abstract).

[21] Bernard D. Steinberg, "Digital beamforming in ultrasound," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 39, no. 6, pp. 716-721, November 1992.

[22] Jian-yu Lu and Jing Wang, "Square-wave aperture weightings for reception beam forming in high frame rate imaging," in *2006 IEEE Ultrasonics Symposium Proceedings* (in press).

[23] J. W. Goodman, *Introduction to Fourier Optics*. New York, N.Y.: McGraw-Hill, 1968, Ch. 2-4.

[24] Jian-yu Lu and Jiqi Cheng, "System for extended high frame rate imaging with limited diffraction beams," United States Patent (filed).

[25] Chihiro Kasai, Koroku Namekawa, Akira Koyano, and Ryozo Omoto, "Real-time two-dimensional blood flow imaging using an autocorrelation technique," *IEEE Transactions on Sonics and Ultrasonics*, vol. SU-32, no. 3, pp. 458-464, May 1985.

[26] Jorgen Jensen and Peter Munk, "A new method for estimation of velocity vectors," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 45, no. 3, pp. 837-851, May 1998.

[27] Jian-yu Lu and John L. Waugaman, "Development of a linear power amplifier for high frame rate imaging system," in *IEEE 2004 Ultrasonics Symposium Proceedings*, 04CH37553C, vol. 2, pp. 1413-1416, 2004 (ISSN: 0-7803-8413-X).

[28] Jian-yu Lu, "A multimedia example," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 50, no. 9, p. 1078, September 2003.