Ultrasonics 54 (2014) 205–216

Contents lists available at SciVerse ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Improvement of ultrasound speckle image velocimetry using image enhancement techniques

Eunseop Yeom [a], Kweon-Ho Nam [b], Dong-Guk Paeng [b], Sang Joon Lee [a,]*

[a] Center for Biofluid and Biomimic Research, Department of Mechanical Engineering, Pohang University of Science and Technology, Pohang, South Korea
[b] Department of Ocean System Engineering, Interdisciplinary Postgraduate Program in Biomedical Engineering, Jeju National University, Jeju, South Korea

ARTICLE INFO

Article history:
Received 16 November 2012
Received in revised form 1 May 2013
Accepted 3 May 2013
Available online 13 May 2013

Keywords:
Ultrasound speckle images
Image-enhancement technique
Blood flow
RBC aggregation

ABSTRACT

Ultrasound-based techniques have been developed and widely used in noninvasive measurement of blood velocity. Speckle image velocimetry (SIV), which applies a cross-correlation algorithm to consecutive B-mode images of blood flow has often been employed owing to its better spatial resolution compared with conventional Doppler-based measurement techniques. The SIV technique utilizes speckles backscattered from red blood cell (RBC) aggregates as flow tracers. Hence, the intensity and size of such speckles are highly dependent on hemodynamic conditions. The grayscale intensity of speckle images varies along the radial direction of blood vessels because of the shear rate dependence of RBC aggregation. This inhomogeneous distribution of echo speckles decreases the signal-to-noise ratio (SNR) of a cross-correlation analysis and produces spurious results. In the present study, image-enhancement techniques such as contrast-limited adaptive histogram equalization (CLAHE), min/max technique, and subtraction of background image (SB) method were applied to speckle images to achieve a more accurate SIV measurement. A mechanical sector ultrasound scanner was used to obtain ultrasound speckle images from rat blood under steady and pulsatile flows. The effects of the image-enhancement techniques on SIV analysis were evaluated by comparing image intensities, velocities, and cross-correlation maps. The velocity profiles and wall shear rate (WSR) obtained from RBC suspension images were compared with the analytical solution for validation. In addition, the image-enhancement techniques were applied to *in vivo* measurement of blood flow in human vein. The experimental results of both *in vitro* and *in vivo* SIV measurements show that the intensity gradient in heterogeneous speckles has substantial influence on the cross-correlation analysis. The image-enhancement techniques used in this study can minimize errors encountered in ultrasound SIV measurement in which RBCs are used as flow tracers instead of exogenous contrast agents.

1. Introduction

A number of ultrasound techniques for velocity measurement of blood flows have been proposed. Among these techniques, Doppler velocimetry has been extensively used in imaging and quantifying blood flows. However, this method only quantifies the axial velocity component of scatter motion. In addition, an aliasing problem restricts the maximum measurable velocity and the angle dependence leads to incorrect velocity measurement [1]. To overcome these technological limitations, a speckle tracking method, which estimates the displacement of blood flows based on B-mode ultrasound images, was proposed [2]. It searches the best matched position between the kernel and the grid of surrounding locations in consecutive B-mode images using normalized correlation or sum-absolute-difference methods. Through this best matched location, the vector of flow motion is obtained for a particular kernel [3–5]. An echocardiography particle image velocimetry (Echo-PIV) technique was developed by combining PIV velocity field measurement technique and B-mode ultrasound contrast imaging [6,7]. It involves identifying and tracking of ultrasound contrast agents (UCAs) in a flow field, and computing of velocity vectors using a cross-correlation algorithm. The Echo-PIV technique has been improved by many researchers under *in vitro* and *in vivo* conditions [6–11]. Meanwhile, ultrasound speckle image velocimetry (SIV), which applied the cross-correlation algorithm to ultrasound images scattered by red blood cells (RBCs), was introduced [12]. The blood flow in the perivalvular area of a human superficial vein was recently investigated using a high-frequency ultrasound system [13]. Similar to the SIV method, the ultrasonic speckle signals

* Corresponding author. Address: Center for Biofluid and Biomimic Research, Department of Mechanical Engineering, Division of Integrative Biosciences and Biotechnology, Pohang University of Science and Technology, San 31, Hyoja-dong, Namgu, Pohang, Gyeongbuk 790-784, South Korea. Tel.: +82 54 279 2169; fax: +82 54 279 3199.

E-mail address: sjlee@postech.ac.kr (S.J. Lee).

0041-624X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultras.2013.05.001

backscattered from moving medium are used to evaluate speckle displacement in ultrasonic speckle velocimetry (USV). However, the USV method uses a time-domain cross-correlation algorithm to backscattered signals of Newtonian suspension. It can measure the flow velocity with high accuracy and good spatial resolution, yet this method entails higher computational cost and longer data collecting time compared with image-based estimation [14–16].

RBCs in plasma aggregate to form rouleaux as a reversible process. RBC aggregation plays an important role in the flow circulation networks and is closely related with various cardiovascular diseases [17–19]. RBC aggregates increase the level of ultrasound backscattering signals and speckle images of blood contain hemorheological information. As the spatial resolution has been improved by adopting a high-frequency transducer [20,21], it is now possible to measure simultaneously the velocity field and RBC aggregation from speckle images of blood. However, RBC aggregation is highly dependent on hemodynamic conditions such as shear rate [22]. Hence, grayscale intensities of speckle images vary along the radial direction of blood vessels. The heterogeneous speckles in B-mode images cause spurious vectors in the cross-correlation analysis of SIV [6,9].

Several image-enhancement techniques have been explored to improve the accuracy of cross-correlation analysis of inhomogeneous particle images. A min/max technique was proposed to enhance intensity variation between particle and background images [23]. In addition, image-enhancement techniques such as thresholding, contrast enhancement, and histogram equalization were utilized [24]. A modified histogram equalization (MHE) technique was developed by combining thresholding and histogram-stretching methods [25]. To enhance PIV results, the background image obtained by averaging a series of images was subtracted [26]. The errors caused by bright spots were minimized through an intensity capping method, which imposes a user-specified upper limit to the grayscale intensity of images [27]. The results were compared with those of other techniques such as MHE, min/max, and contrast-limited adaptive histogram equalization (CLAHE). CLAHE is an adaptive contrast-enhancement method that transforms pixel intensity by referring to a local intensity histogram.

In this study, CLAHE, min/max, and subtraction of background image (SB) methods were applied to speckle images to investigate their effects on the measurement accuracy of the ultrasound SIV technique. Analytic parameters, vector field, and the cross-correlation map obtained from the original B-mode images were compared with those obtained from processed images. In addition, the velocity profiles and wall shear rate (WSR) of RBC suspension were measured using the SIV method combined with the image-enhancement techniques. The results were compared with the analytic solution to confirm the distortion that can be induced. Finally, the feasibility of the proposed techniques was assessed by applying them to blood flows in a human vein. It would be helpful to accurately measure the velocity information without exogenous tracers.

2. Materials and methods

2.1. Experimental setup

Experiments were performed using the experimental setup shown in Fig. 1. An ultrasound imaging system equipped with a 35-MHz mechanical sector-scan probe (Capistrano Labs., San Clemente, CA, USA) was employed to obtain ultrasound speckle images. The transducer has a diameter of 5 mm and a focal length of 11.8 mm. The transducer chamber was filled with degassed water and covered with a thin membrane made of syndiotactic 1,2-polybutadiene. An ultrasound imaging board (PCB v4.2, Capistrano Labs., San Clemente, CA, USA) with a pulser/receiver and a servo controller was installed in a personal computer and connected to the probe. The center of the vessel was positioned at the focal point of the transducer. Speckle images were acquired at a frame rate of 50 Hz with a sector angle of 20°.

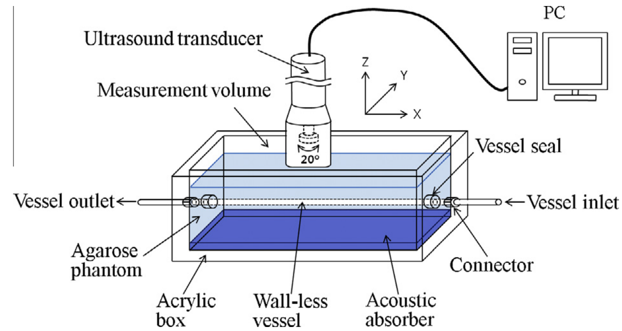

Fig. 1. Schematic diagram of the experiment setup and vascular phantom used for ultrasound imaging.

2.2. Vascular phantom

To minimize acoustic artifacts caused by the reflection of the tube wall, all data were acquired from a vascular phantom placing acoustic absorber at the bottom of the acrylic box, as shown in Fig. 1. The vascular phantom was formed by pouring 2% agarose (Sigma Chemical, No. A-9539) gel around a silicone tube connected the side holes of the acrylic box. After confirming the hardening of the gel, the silicone tube was removed to create a lumen with an inner diameter of 2.5 mm. The acoustic velocity and the sound attenuation of the vascular phantom are about 1508 m/s and 7.9 dB/mm, respectively. The attenuation was estimated by using the equation $A(f) = 0.146f^{1.77}$, where f is the central frequency of the transducer [28]. The pressure of blood passing through the wall-less vessel tends to pull the phantom away from the inlet and outlet of the tube, resulting in a leak. To prevent such leaks at the inlet and outlet, two cylindrical seals with a length of 0.6 mm and a diameter of 0.6 mm were glued to the side walls of the acrylic box, as shown in Fig. 1. Connectors were used to couple the flow loop with the agarose phantom. The measurement volume was immersed in distilled water for ultrasound transmission.

2.3. SIV analysis

Ultrasound B-scan data consisting of 128 A-lines were acquired using an ultrasound transducer, and then converted into B-mode images. Similar to the conventional PIV method, speckle images were divided into lots of interrogation windows, and a cross-correlation algorithm was applied to consecutive interrogation windows to estimate blood-flow velocity. The cross-correlation coefficient $R(k, l)$ used to evaluate the resemblance of speckle patterns between two consecutive images is given by:

$$R(k,l) = \frac{\sum_{x,y}[f(x,y)-\bar{f}][g(x+k,y+l)-\bar{g}]}{\left\{\sum_{x,y}[f(x,y)-\bar{f}]^2\sum_{x,y}[g(x+k,y+l)-\bar{g}]^2\right\}^{1/2}}, \quad (1)$$

where $f(x, y)$ and $g(x, y)$ indicate the intensity at location (x, y) in the interrogation window of successive image frames, $\bar{f}$, $\bar{g}$ are the average intensities in the windows, (k, l) is the local position in the correlation plane.

The position of the peak value in the correlation plane identifies the average displacement in the interrogation window. Several methods have been used to increase the dynamic range for subpixel analysis. The present study adopted the three-point Gaussian