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Improvement of estimation parameter for frame-rate analysis of blood flow using laser speckle image sensing

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ABSTRACT

Improved estimation parameters are proposed for frame-rate analysis of blood flow in skin tissue and a blood vessel using laser speckle image sensing. These parameters are introduced for visualizing a blood flow distribution with improving image quality and computation time or with reducing effects of a speckle contrast and random noises. Experiments were conducted for sample models using ground-glass plates and fluid flow, human finger, human wrist and an anesthetized rat to confirm the feasibility of the proposed parameters.

1. Introduction

The monitoring of blood flow in skin tissue is a powerful tool for analyzing the condition of living bodies or the health state. A change of blood flow may be an indicator of a disease or may result from various diseases. Therefore, various types of techniques for blood flow imaging have been proposed and tested in many medical fields such as ophthalmology, dermatology and internal medicine. Especially, we have been interested in the techniques for visualizing the blood flow distribution by means of bio-speckle fluctuations [1,2], which can easily be observed from living bodies under illumination of laser light in the form of a temporal variation of laser speckle patterns, and have widely been applied to noncontact and noninvasive means for elucidating the living dynamics of bodies. The intensity fluctuation of laser light from biological specimens was first studied by Briers [3], and then, the visualization of retinal blood flow distribution using laser speckle photography was performed by Fercher and Briers [4,5]. Dunn et al. [6] also proposed a method for dynamic imaging of cerebral blood flow by means of bio-speckles. After that, several blood flow imaging techniques based on an intensity difference in a temporal sequence of bio-speckles were studied by Fujii et al. [7,8], Aizu et al. [9–12], Konishi et al. [13,14], and Yokoi et al. [15,16]. There are many estimation parameters proposed so far for bio-speckle image analysis such as the average derivative (AD) by Konishi et al. [13], the square blur rate (SBR) and the mean blur rate (MBR) by Konishi et al. [14], the time history of the speckle pattern (THSP) and the width of the equivalent rectangle (WER) by Rabal et al. [17], the generalized differences (GD) and the weighted generalized differences (WGD) by Arizaga et al. [18], the speckle flow index (SFI) by Choi et al. [19], the contrast-to-noise ratio (CNR) by Murari et al. [20], the decorrelation factor (DCF) by Yokoi et al. [15] and, the modified temporal contrast factor (MTCF) and the modified inversed temporal contrast factor (MITCF) by Yokoi et al. [16]. The above techniques are widely utilized for various biomedical applications such as imaging of rat cerebral blood flow [21], monitoring of the blood perfusion in mesenteric microvessels of the tumor mouse [22], imaging of rat cortical hemodynamics [23] and, visualizing the dynamics of small intracellular particles in live biological cells extracted from the rat brain [24]. Most of them, however, require several speckle images in a temporal sequence to obtain a blood flow map, because they are based on a temporal statistics of intensity fluctuations in bio-speckles.

As a technique for measurement of blood flow speed, a laser Doppler flowmetry (LDF) [25] is also well known, which is widely applied for clinical studies on the human brain [26], retina [12,27,28], and skin [29]. The laser speckle technique and the LDF are both based on dynamic light scattering phenomena. What is detected is, however, different due to their different signal detecting principles: the former is random intensity fluctuations

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and the latter is periodic beat signals, even if the phenomena are essentially equivalent. There are some interesting discussions on this subject [30,31]. We consider that laser speckle technique is based on an area detection and the LDF is based on a point detection. The area detection may be much desirable in medical applications, thus, we adopt the laser speckle technique as a tool for visualizing blood flow in the present study. The laser speckle technique measures not an absolute but a relative blood flow speed, nevertheless, it is a useful tool in a medical diagnostic environment.

In the present study, we first propose a reciprocal spatial difference (RSD) [32] as an estimation parameter for improving the image quality and computation time in blood flow imaging using the SFI [19], which is based on a traditional laser speckle imaging approach [4]. Both the SFI and the RSD are proposed for frame-rate imaging of blood flow, however, they are based on different algorithms in image processing. The SFI is based on a standard deviation of the spatial intensity variations in the speckle pattern, while the RSD is based on a spatial difference value of the speckle pattern. According to our comparative experiments, the RSD seems to be superior to the SFI in image quality and computation time. This fact suggests that the RSD can visualize the spatial distribution of the blood flow speed in a frame rate with better image quality and less computation time in comparison with the SFI. In computing RSD, sequential speckle patterns are first stored into PC memory and, then, processed to derive sequential blood flow distribution maps in the frame rate which is the same one of original speckle patterns. We next propose a modified reciprocal spatial difference (MRSD), which is an extension of the RSD and can reduce the effects of the speckle contrast and random noises on the blood flow images. Experiments with sample models using ground-glass plates and fluid flow are first performed to evaluate relations of RSD or MRSD versus speed and, then, experiments for the human finger, human wrist and the anesthetized rat are conducted to show the feasibility of the RSD and MRSD for frame-rate analysis of the blood flow. In the above experiments, the SFI, RSD and MRSD images are suitably compared with each other on image quality and computation time.

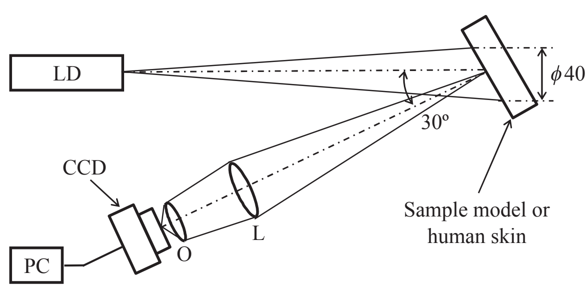

Fig. 1. Schematic diagram of the optical system for detection of speckle images.

2. Principle

Fig. 1 shows a basic optical system used in this study for detecting speckle patterns. A near-infrared laser diode (LD) (MINI-830F-50-C, PHOTOTECHNICA, Japan) with a wavelength of 830 nm, irradiance of 6.4 kW/m^2, and coherence length of approximately 20 cm) is used as a laser source. Light from the LD directly illuminates the object to be measured with a circular region of nearly 40 mm in diameter. The scattered light from the object passes through a lens L with a focal length of 100 mm and an objective O with magnification of 5 and, then, reaches a video-rate CCD camera (XC-ST30, SONY, Japan) with a pixel size of 14 μm and window size of 4.5 mm × 3.5 mm, by which a speckle pattern is observed. A personal computer (PC) is used for analyzing and displaying a relative speed distribution of the object by processing the observed speckle patterns. The optical system in Fig. 1 is employed in experiments conducted for a sample model using ground-glass plates and the human finger and wrist. In experiments conducted for the anesthetized rat, another optical system is employed, which is shown later in the present study.

As the object moves, the speckle pattern fluctuates temporally and spatially. The faster the object moves, the more rapidly the speckle pattern varies in intensity. When the speckle pattern is recorded by the CCD camera that has a finite integration time, it is clear that some of the fluctuations in speckle intensity are averaged out and the speckle pattern is blurred.

To estimate the local speed of the moving object by means of the blur of the speckle image, we introduce a processing unit into image data, which is a square of pixels as shown in Fig. 2a. The processing unit can be used for quantitative estimation of the blur of the speckle image. The RSD at the processing unit of $p \times p$ pixels in size can be given as

$$RSD = \frac{\left[\left\{\sum_{x=1}^{p}\sum_{y=1}^{p} I_{x,y}\right\}/p^2\right]^2}{\left[\left\{\sum_{x=1}^{p}\sum_{y=1}^{p} (I_{x,y} - I_{0.5(p+1),\,0.5(p+1)})\right\}/(p^2-1)\right]^2}. \quad (1)$$

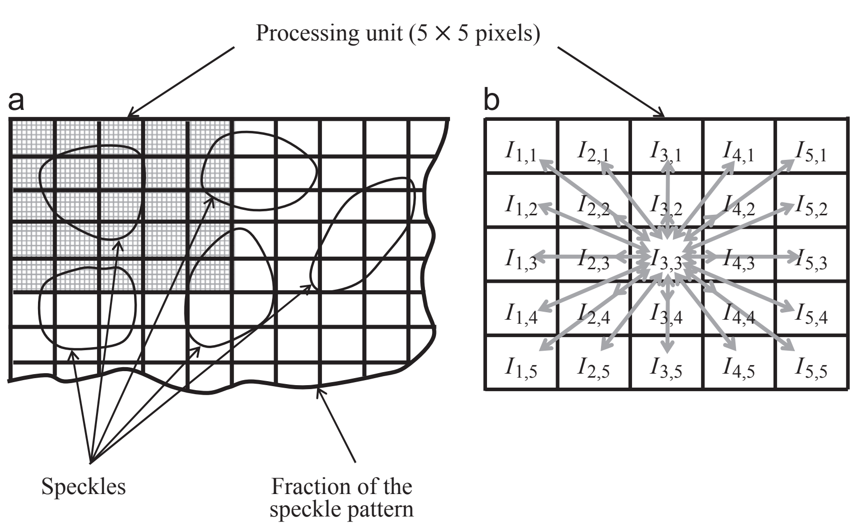

Fig. 2. (a) Illustration of the processing unit used for the calculation of RSD and (b) schematic diagram for calculation of RSD.