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Monitoring capillary blood flow using laser speckle contrast analysis with spatial and temporal statistics

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ABSTRACT

Laser Speckle Contrast Imaging (LSCI) is a simple and powerful technique that is used for full-field imaging of blood flow. The technique analyzes fluctuations in a dynamic speckle pattern to detect the movement of particles. In this article Laser speckle contrast analysis based on spatial and temporal correlations (sLASCA and tLASCA) were used to provide a velocity map of the area of interest in real time without the need for scanning. Spatial and temporal laser speckle contrast analysis have been shown to be a viable real-time method for detecting variations in blood flow. The results of some initial experiments on volunteers are presented. Both the techniques namely sLASCA and tLASCA are able to pick up changes in blood flow, which may arise due to various physiological conditions. Further, more blood flow reflected due to less skin thickness was sensed by the tLASCA technique which can be put to good use in the follow-up of the treatment of certain diseases which may cause decreased blood flow. Thus, both the techniques can be used to compare differences in blood flow values at region in normal subjects and in diseased subjects.

1. Introduction

Monitoring of blood flow in capillaries can be of great interest to clinicians in the diagnosis of vascular diseases. In this regard, laser Speckle Contrast Imaging (LSCI) is a simple and powerful technique that is used for full-field imaging of blood flow in vivo without scanning [1–4]. The technique analyzes fluctuations in a dynamic speckle pattern to detect the movement of particles similar to how laser Doppler analyzes frequency shifts to determine particle speed. LSCI accesses the speed information of the scatterers by calculating the speckle contrast [5,6], which is defined as the ratio of the standard deviation of intensity to the mean value of intensity in the speckle patterns.

Briers and Webster [7–9] in 1995 developed a digital version of single speckle photography called Laser Speckle Contrast Analysis (LASCA).

However, because the contrast is analyzed for a group of pixels in one image, LASCA lacks spatial resolution. To overcome this disadvantage, Cheng et al. [13] developed Laser Speckle Imaging (LSI) into which the contrast is calculated based on one pixel in a time sequence, rather than based on multiple pixels in one image as is schematically shown in Fig. 1(a). LSI, therefore, is the temporal equivalent of LASCA.

Likewise, several researchers [10,13–17] have developed techniques which are combinations of LASCA and LSI. Forrester et al. [14,15] developed laser speckle perfusion imaging (LSPI), Konishi et al. [16] developed Laser speckle flowgraphy (LSFG).

Le et al. [10] presented spatial equivalents of LASCA under the name sLASCA. They also introduced tLASCA as temporal equivalents of LASCA, a technique in which averaging in the spatial domain is performed on contrast maps obtained using LSI. They showed that tLASCA give better results and is faster than sLASCA and LSI. Qiu et al. [18] combined both the spatial and the temporal statistics for imaging blood flow with maximized speckle contrast.

Therefore, in this paper, the sLASCA and tLASCA techniques have been used to monitor capillary blood flow in human hands under different conditions and the results have been compared.

2. Experimental techniques and setup

2.1. Laser speckle imaging

Laser speckle is random interference pattern produced by coherent addition of scattered light with slightly different path lengths. This random interference patter can be captured on camera when an area is illuminated by a laser beam.

When an object moves, the speckle pattern it produces changes. For short movements of a solid object, the speckles move with the object and they remain correlated. For longer movements, they decorrelate and the speckle pattern changes completely [9].

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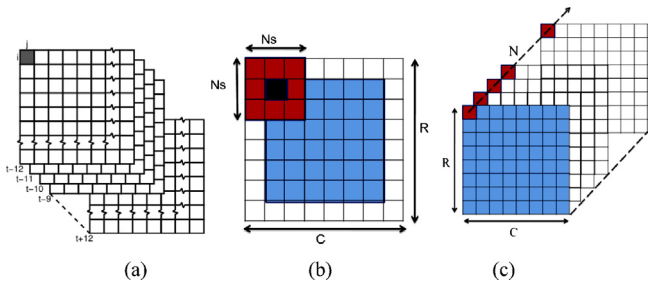

Fig. 1. (a) schematic overview of the way the contrast is calculated in LSI. In pixel (i,j) the contrast is calculated as the ratio of the standard deviation of the intensity at this pixel at different times, and the mean intensity for this pixel. Schematic diagrams of methods for laser speckle contrast analysis based on (b) spatial statistics, and (c) temporal statistics. The $R \times C$ arrays represent the original speckle images. The elements with red color represent the pixels involved in the calculation of the local speckle contrast of the pixel with black color. The blue colored squares represent the derived speckle contrast images. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Decorrelation also occurs when the light is scattered from a large number of individual moving scatterers, such as particles in a fluid.

If the light scattering particles are in motion, a time varying laser speckle is produced at each pixel on the captured image. Assuming ideal conditions for producing the speckle pattern – a single frequency laser and a perfectly diffusing surface with a Gaussian distribution of surface height – it can shown that the standard deviation (SD) of the intensity variations is equal to the mean intensity [9]. Hence, quantitative blood flow information can be obtained by the spatial intensity variations of the speckle contrast varying from 0 (due to rapidly moving particles) to 1 (stationary particles). In the following sections, background mathematical derivations are reviewed and the applications of them in various image processing techniques are discussed in Sections 2.2 and 2.3.

(1) *Speckle contrast*, K: The speckle contrast for a center pixel is computed using the speckle intensity distribution obtained from an $M \times M$ window of surrounding pixels [9].

$$K = \frac{\sigma_s}{\langle I \rangle} \tag{1}$$

where K, σ_s, $\langle I \rangle$ are the speckle contrast, the spatial SD, and the spatial mean intensity of a window of pixels, respectively. As a result, the effective resolution of the contrast image will be reduced by factors of M in each dimension of the original image. It has been reported that a 5×5 or 7×7 pixel window is used to generate the spatial statistics. In this paper, we relook at the use of 3×3, 9×9, 11×11 and 13×13 pixel windows to see how valid its statistics are, and how well its resulting speckle contrast is viewed.

(2) *Decorrelation time*, τ_c: Assuming that the scattering particles (in this case red blood cells) are of uniform size and have Newtonian flow, the speckle contrast K of a time-integrated speckle over the CCD integration time T is given by [11]

$$K = \left\{ \left(\frac{\tau_c}{2T} \right) \left[1 - \exp\left(\frac{-2T}{\tau_c} \right) \right] \right\}^{1/2} \tag{2}$$

where τ_c is the decorrelation time of the intensity fluctuations.

(3) *Mean flow velocity*, v_c: The relationship between τ_c and mean flow velocity, v_c given by [9]

$$v_c = \frac{\lambda}{2\pi\tau_c} \tag{3}$$

where λ is the wavelength of the laser light used. As the $\lambda/2\pi$ term is kept constant, the mean velocity is directly proportional to $1/\tau_c$. Since the wavelength used is 632.8 nm and π is known, we have $v_c = 0.10/\tau_c$ μm/s. A more complicated approximation given by Bonner et al. [12] that takes particle size into consideration calculates valocity as $v_c = 3.5/\tau_c$ μm/s. From the statistically obtained value K in (1) and the relationship in (2), $1/\tau_c$ can be derived to estimate scatterers velocity v_c in the application of LASCA.

K is proportional to $\log(\tau_c/T)$, where as velocity v_c is proportional to $1/\tau_c$. Therefore, K, via τ_c, possesses a "log-inverse" relationship to scatterers velocity v_c.

In the following paragraphs, two reported K-value speckle image processing techniques are described in Sections 2.2 and 2.3.

2.2. Spatially derived contrast using temporal frame averaging (sLASCA)

sLASCA [13] is an improvement of the basic LASCA technique. In the LASCA technique, the speckle contrast for a center pixel is computed using the intensity distribution obtained from an $M \times M$ window of surrounding pixel values using (1). On the other hand, in sLASCA, the derived contrast are further averaged over a predetermined number of raw speckle images.

If $K_{i,j,1}$, $K_{i,j,2}$,...,$K_{i,j,n}$ denote the respective consecutive contrast values at pixel (i,j) in frame 1,2,...,n, the contrast K_{sLASCA} is given by

$$K_{\text{sLASCA}} = \frac{\left(K_{i,j,1} + K_{i,j,2}, + \cdots + K_{i,j,n} \right)}{n} \tag{5}$$

After the computation of K_{sLASCA} values, the resulting image is contrast – streched and converted to a color-mapped image for display.

2.3. Temporally derived contrast (tLASCA)

It is based on the first-order temporal statistics of time-integrated speckle pattern called tLASCA. tLASCA works on the statistics along n frames in the temporal dimension [10]. Therefore, it is able to maintain both display and effective resolution of an image. Also, as long as the number of temporal statistics is adequate, the spatial window size M does not affect the validity of the contrast values.

Thus laser speckle contrast analysis using temporal correlation (tLASCA) is a technique in which averaging in the spatial domain is performed on contrast maps obtained using LSI [10]. For each frame, the contrast value K_{tLASCA} of pixel (i,j) of a particular frame is computed by

$$K_{tLASCA(i,j)} = \frac{1}{M \times M} \sum_{r=i-1}^{i+1} \sum_{c=j-1}^{j+1} \frac{\delta_{i,j,t}}{\left\langle I_{i,j,t} \right\rangle} \tag{6}$$

where $\delta_{i,j,t}$ is the standard deviation of all pixels at (i,j) and $\left\langle I_{i,j,t} \right\rangle$ is the mean intensity of all pixels at (i,j) in n frames along the temporal dimension, and K_{tLASCA} is calculated as an average over a $M \times M$ spatial observation window. It is noted that the number of pixels involved in a $M \times M$ pixel observation window using tLASCA is $(M)(M)(n/2)$, where n is the number of temporal frames. This small window of observation insures good statistics while not including statistics of slower moving or nonmoving particles. After the computation of K_{tLASCA} values, the resulting image is contrast streched and converted to color-mapped image for viewing.

Table 1 summarizes the methods used in monitoring blood flow. Fig. 1(c) presents the speckle contrast calculation using temporal correlation.

2.4. Experimental setup

The schematic of the experimental setup used for the sLASCA and tLASCA analysis is shown in Fig. 2. A beam of He–Ne laser