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Impact of the β Correction Factor on the Accuracy of Laser Speckle Contrast Imaging Measurements

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Abstract: We investigate a method for correcting laser speckle imaging (LSI) measurements, enabling consistent Speckle Flow Index (SFI) comparison across LSI systems. Implementing β correction significantly reduces SFI differences in identical samples analyzed with different setups.

1. Introduction

For laser speckle imaging (LSI) of blood flow, achieving consistency in data is crucial, both across various LSI systems and over different time points with the same system. Ideally, consistent speckle contrast results from the same sample using different LSI setups can be achieved through a standardized process. A key aspect of this standardization is the β coefficient, which acts as a correction factor influenced by the system's settings, such as speckle size or light polarization. Common practice simplifies the β coefficient to 1 for cross-polarized and 0.5 for unpolarized detectors [1,2]. However, this approach can lead to significant errors, as external factors [3] prevent the β coefficient from realistically reaching 1. Therefore, pre-calculating the β coefficient can enhance the accuracy of LSI measurements. By adjusting hardware parameters and applying the measured β coefficient, we demonstrate possible the possibility to achieve comparable blood flow measurement. This approach can ensure more reliable and consistent data collection in LSI blood flow measurements.

2. Materials and Methods

2.1. LSI system

For LSI, the degree of blurring of the speckle pattern is measured by the local speckle contrast (K) [4], defined as the ratio of the standard deviation (σ) to the mean intensity (⟨I⟩) of pixels within a sliding window: $K = \sigma/\langle I\rangle$
In this study, the LSI setup (Fig. 1) comprised a 785-nm long-coherence laser, a CMOS detector (FLIR Blackfly S USB3), and a laptop. Polarization of the laser source and detector was adjusted using two linear polarizers and a set of neutral density filters (NDFS) (optical density 0.1-0.6) were employed for intensity modulation. The speckle pattern was captured using the CMOS detector and data processing was performed in MATLAB. The β coefficient, vital for the analysis, was derived from an image of a static phantom using the formula: $\beta = K^2$. The Speckle Flow Index (SFI), which quantifies the flow of optical scatterers, was calculated using the formula [5]: $SFI = \beta/(2TK^2)$, where T is the exposure time of the CMOS camera. Here, we used T = 10 ms.

2.2. Phantom Imaging

For this study, a static PDMS phantom was used with an embedded 656-µm-diameter glass capillary tube. Intralipid flow was performed at 1-5 mm/s with an infusion pump.

Imaging phantoms with a change in polarization. The measurement process was conducted in two stages. Initially, the light intensity captured by the camera was adjusted by rotating the polarizer attached to the laser source. This was done in increments of 10 degrees, ranging from 0 to 60 degrees, with each increment approximately resulting in a 10% decrease in light intensity. Six separate measurements were taken at these orientations. In the subsequent stage, the polarizers were removed. NDFs were then utilized to replicate the light

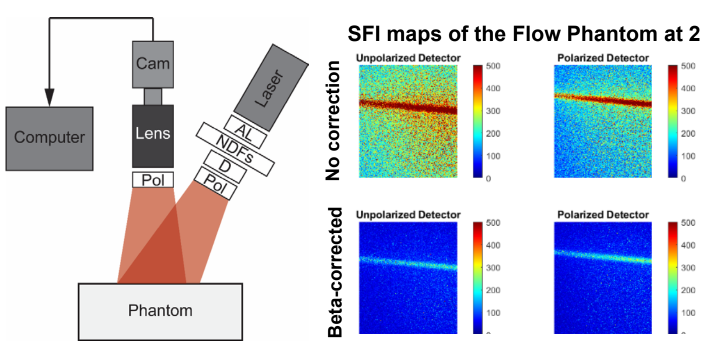

Fig. 1. (a) Schematic of the custom LSI system used in this study. Pol – polarizer, AL – aspheric lens, NDFs – neutral density filters, D – diffuser. (b) Images of a flow phantom with the flow speed of 2 mm/sec. Without β correction (top row), the SFI maps showed a dependency on the polarization of the detector. Images with β correction (bottom row) had similar SFI values for both the polarized and unpolarized detection schemes.

intensities observed in the first part of the experiment to ensure that the light intensity change did not affect the measurement. The β values, derived from measurements using a static phantom, were subsequently applied to correct the measurements obtained from the flow phantom.

2.3. Imaging phantoms with different f-number settings

The speckle size depends on the laser wavelength, the magnification setting, and the aperture size [6]. To adjust the aperture, we first altered the aperture settings, decreasing the light intensity by about 10% at each step. We then maintained a constant f/# and matched the light intensities to those achieved in the first part using neutral density filters (NDFs).

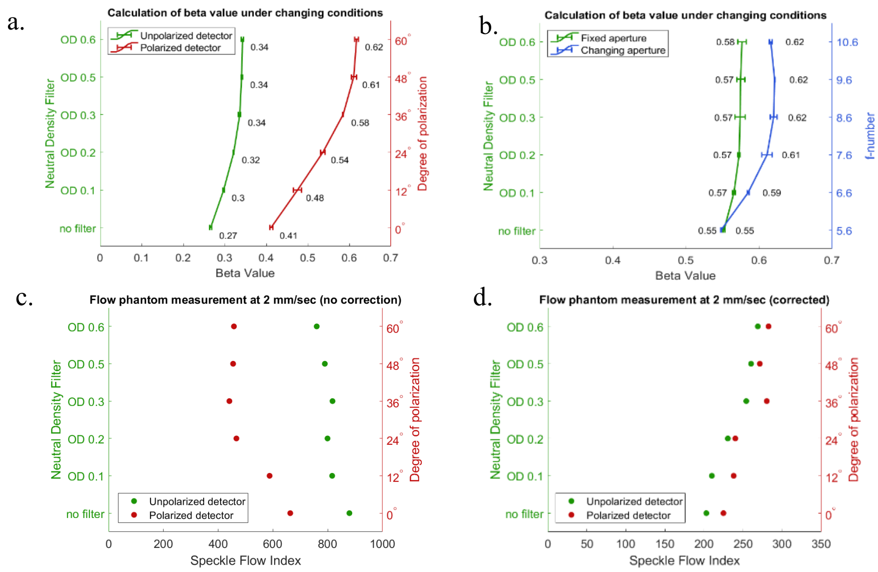

Fig. 2. Experimental measurement of β coefficient and SFI. (a) Effect of detector polarizer on β. (b) Effect of aperture diameter on β. (c) Uncorrected and (d) corrected flow measurements with the use of β. Data at 2 mm/s flow speed are shown as a representative example.

3. Results

Switching the detector from a polarized to non-polarized state typically halves the β values [1]. We observed an average reduction of 35% in the β values from the static phantom for unpolarized detection compared to cross-polarized detection (Fig. 2a). Reducing the aperture increase β values by 3.5% to 9% (Fig. 2b) With the flow phantom, placing a polarizer on the detector increased the detected SFI by 33% to 63% (Fig. 2c). Furthermore, adjusting the polarization degree at the source led to a 65% variation in the SFI at a 60-degree polarization compared to 0 degrees (Fig. 2c). By accurately measuring the β coefficient and subsequently adjusting the SFI calculations with it, we noted that the discrepancy in measured SFI between polarized and non-polarized detectors was only 17% (Fig. 2d).

4. Conclusion

This study demonstrates the importance of β measurement for the correct calculation of the speckle flow index and for the ability to produce standardized SFI maps. It was also shown that varying system parameters such as light polarization and speckle size greatly affects SFI values, while change in light intensity on itself does not impact speckle measurements.

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