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# Estimation of flow rate and direction of medium with low scattering coefficient via linear polarization measurement

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ABSTRACT

Many biological systems involve flow of various types of liquids. Estimation of the rate and direction of the flow is highly important for a large number of bio-medical related applications. The working point discussed in this paper involves a medium with a relatively low scattering coefficient such that the polarized light going through it is not depolarized, but rather modifies its polarization state instead. An experimental validation is presented, which shows that illuminating flow in a medium with linear polarized light, and measuring the change in polarization state at the output of the medium, can correlate highly with the direction and flow rate through that medium. By inspecting the spatial shape change in the spot of light, and the change of polarization state in relation to different integration times as well, the direction and flow rate can be fully extracted.



## 1. Introduction

Flow of blood, milk and other liquids is very common in many biological systems. Examples include arterial blood flow; milk through the nipple of a breastfeeding mother and water-like liquids such as tear drops in eyes. In various applications, the estimation of flow rate and direction is highly important, for example, estimation of amount of blood going through the principal artery in the neck or earlobe [1] and estimation of amount of milk going through the nipple of the breast [2].

Previous works demonstrated that when a polarized light goes through highly scattering tissue, the light becomes depolarized [3,4]. This work is conducted under a different assumption – a thin tissue with a relatively small amount of scattering ($\mu_s = 1\ \mathrm{mm}^{-1}$). The light exiting the tissue is shown not to lose its polarization (in thin biological tissue of a few mm), but its state of polarization changes. This change, as well as the spatial shape of the beam going through the tissue, is highly dependent upon the direction and the flow rate. By externally measuring the two parameters (polarization state and spatial shape of the beam) in the inspected tissue in relation to integration time, flow characteristics can be estimated.

Several techniques are used to approach the above mentioned problem of estimation by using Doppler effect [5,6] (e.g. for estimation of axial and transverse components of flow). Other approaches for estimation of flow involve using mechanical properties of soft tissue [7] or intra-ventricular injection of radiotracer, for imaging the distribution of blood flow with positron emission tomography [8] or inert radiotracers [9]. Use of bolus signals obtained from tissue as reference functions, rather than arterial input functions, when deriving cross-calibrated cerebral blood flow estimates via deconvolution, are shown in Ref. [10]. Use of delivered heat and temperatures during hyperthermia treatment of patients at several points in the tissue for estimating the tissue parameters such as the blood perfusion rate are shown in Ref. [11]. Other techniques involve optical concepts, e.g., approaches based on speckle pattern processing [12,13], however those optical techniques are better at extracting flow along certain directions (i.e. *X* direction) and are more problematic at estimating flow along other directions (i.e. *Y* direction).

It is important to note that ultrasound Doppler imaging can also estimate flow [6]. However, the spatial resolution obtainable with ultrasonic imaging is orders of magnitude lower than the one obtainable by the simple optical realization proposed. Other optical techniques, such as optical coherence tomography (OCT), show similarity in obtainable resolution [14]. However, OCT requires much more complicated optical configuration and is limited in the axial range it can map.

The paper is constructed as follows: Section 2 describes materials and methods used. Section 3 experimentally validates the approach and presents experimental results. Section 4 presents physical explanation and the matching between measured results and the intuitive physical model. Conclusions appear in Section 5.

## 2. Materials and methods

An experimental setup was built, mimicking blood flow in the body for measuring polarization of transmitted light intensity.

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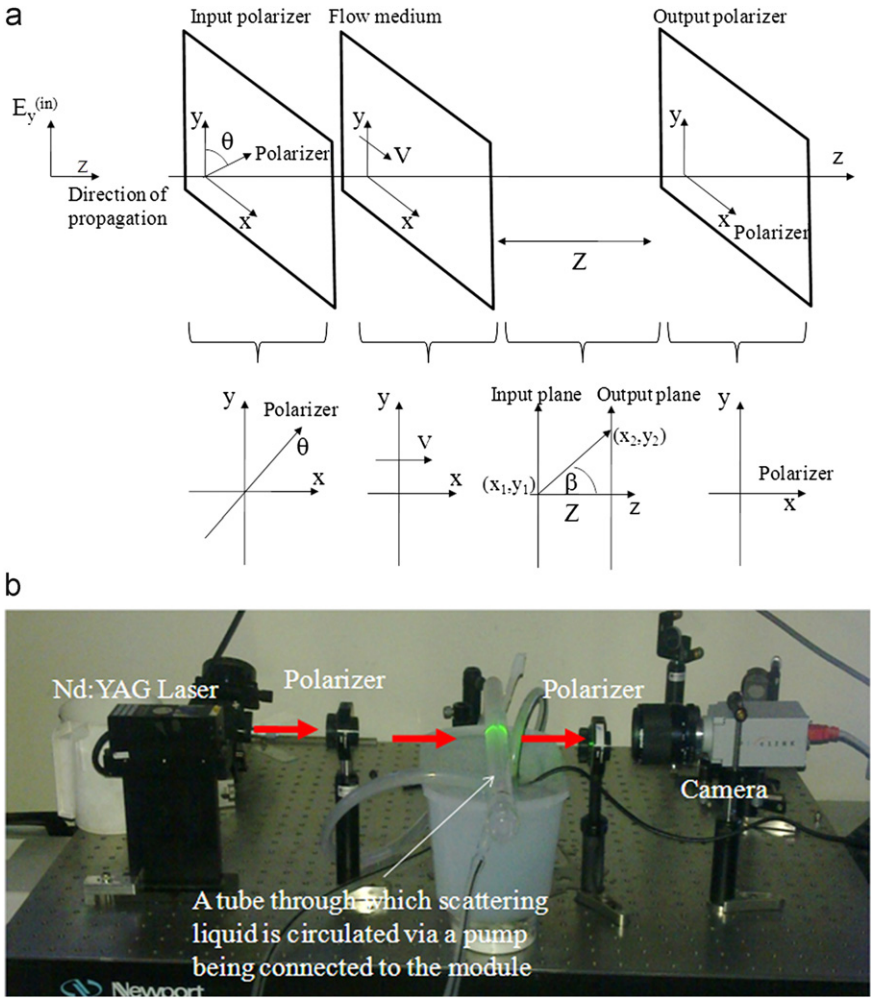


**Fig. 1.** Schematic sketch of experimental setup (a) and image of experimental setup (b) including laser, first polarizer, flow system, second polarizer (analyzer) and camera.

This model assumes a light polarized along the *y*-axis which illuminates a polarizer positioned at an angle of $\theta$ to the *y*-axis and a medium flowing at $v$ velocity along the *x*-axis. A propagation of Z distance from the beginning of the flow medium until the light reaches the output plane where an analyzer is positioned along the *x*-axis is described in the schematic sketch of Fig. 1a. The setup includes a pump and a closed-loop, 3 cm diameter glass pipe. The image of the experimental system is presented in Fig. 1b. The polarizer and the flowing medium distance was 6 cm and the detector was focused on the analyzer (real distance of 2.5 cm). The numerical aperture (NA) of the imaging lens was 0.2. For beam shaping measurements, the analyzer was removed.

Diluted milk [15] and intralipid 20% (IL, Lipofundin MCT/LCT 20%, B. Braun Melsungen AG, Germany) were used as scattering media. Correlation between intralipid concentration and scattering properties was calculated based on Zaccanti et. al. [16] and re-measured by us [17]. The different scattering values were prepared in order to mimic the optical properties of real biological tissue (not blood) at the range of 1–35 $mm^{-1}$ with anisotropy of 0.8 leading to effective scattering coefficient values of 0.2–7 $mm^{-1}$ [18,19]. Diluted milk, as well as intralipid in water flow inside the glass pipe and demonstrate low scattering medium flow.

Thus, one needs to note that the scattering was done by passing the light via the liquid (water mixed with milk or with intralipid) pumped through the tube. By controlling the amount of milk/intralipid in the liquid, the amount of scattering was controlled. The tube with the scattering liquid imitates flow in tissue. Other than the experiment performed with flowing liquid, no additional tissue caused scattering.

The experimental system (Fig. 1b) features a green doubled Nd:YAG laser at wavelength of 532 nm (Fig. 1b left) which illuminates the sample after passing through a polarizer. The light passing through the pipe is captured using a Pixelink PL-A741-E camera (PixeLINK, Ottawa, ON) with pixel size of 7 μm × 7 μm (Fig. 1b right).

The captured video is analyzed by MATLAB (The MathWorks, Natick, MA) software.

## 3. Experimental results

### 3.1. Static measurements

First the polarization of light that passed through the scattering medium was measured. Different concentrations of scattering liquids were tested. This was done in order to set the working point of this research. We looked for a medium with a relatively small scattering coefficient, such that the polarized light going through it is not depolarized.

In Fig. 2 one can see representative results for four different scattering coefficients. When no sample was inserted between the polarizer and the analyzer, no light was collected by the camera, and the polarization state (the normalized intensity along the direction of the analyzer) remained 1 ($\mu_s=0$ in Fig. 2). When