Laser speckle contrast imaging of the skin: interest in processing the perfusion data

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Abstract Laser speckle contrast imaging (LSCI) is a recent clinical powerful tool to obtain full-field images of microvascular blood perfusion. The technique relies on laser speckle obtained by the interactions between coherent monochromatic radiations and the tissues under study. From these speckle images, contrast values are determined and instantaneous map of the perfusion are computed. LSCI has gained increased attention in the last years and is now additional to laser Doppler flowmetry (LDF). In spite of the growing interest for LSCI in skin clinical research, very few LSCI perfusion data processing have been published from now to extract physiologically-linked indices. By opposition, numerous signal processing works have been dedicated to the processing of LDF signals. The latter works proposed methodological processing procedures to extract information reflecting underlying microvascular mechanisms such as myogenic, neurogenic and endothelial activities. Our goal herein is to report on the potentialities of studies dedicated to the processing of LSCI perfusion data. Linear and nonlinear analyses could be of interest to improve the understanding of LSCI images.

Keywords Laser speckle contrast imaging · Microcirculation · Signal processing · Image processing · Laser Doppler flowmetry

In clinical research, the real-time monitoring of skin microvascular blood perfusion can be performed, among others, with laser Doppler flowmetry (LDF) and laser speckle contrast imaging (LSCI) (see, e.g., [7, 13, 18, 26, 43, 46]). LDF has been proposed in the 1970's [45] to monitor the microvascular blood perfusion in a small volume of tissue (approximately 1 mm³ in skin when a 780 nm laser wavelength is used). Since that time, many works have led to the improvements of the technique (see, e.g., [1–6, 10, 29, 38, 39, 47]). LSCI is a more recent technique developed in the mid 1990s. It relies on the speckle phenomenon generated by the interactions between coherent monochromatic radiations and a scattering medium [7]. The first speckle imagers were commercialized very recently and from this time LSCI has been the subject of an increasing number of papers (see, e.g., [7, 30, 31, 40]). LSCI and LDF have found widespread skin vascular application among which we can cite the reperfusion monitoring of skin flaps, the quantification of peripheral vascular diseases, the perfusion monitoring of burns, wounds and foot ulcers. LSCI has the advantage, over LDF, of being a noncontact method and giving a two-dimensional image of the perfusion, thus reducing the spatial variability of the measure [42].

In the last years, several LDF models and simulations [9, 16, 22–24, 27, 35–37] and many LDF signal processing studies have been published. A number of these signal processing works use wavelets to extract data from the heart rate, respiration, myogenic, neurogenic and endothelial activities (see, e.g., [12, 17, 44]). Other works

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proposed fractal or multifractal analyses to better understand LDF signals (see, e.g., [15, 21, 28]). Moreover, as the LDF technique is very sensitive to movements, signal processing to reduce the movement artifacts have also been published [19, 20, 25]. Furthermore, some authors analyzed the sample entropy of LDF signals from healthy subjects and from patients with systemic sclerosis [8]. This list of signal processing works performed on LDF data is not exhaustive but shows that a high number of studies took advantage of the signal processing capacities to go forward in the understanding of LDF signals. From all these works, diagnosis approaches have also become easier.

For LSCI data, images can be processed into two ways: either the images are processed, one by one. In that case, image processing tools are used and spatial informations are processed and then studied with time evolution (comparing the results from one image to the others); either pixels values are averaged over an area, called region of interest (ROI) [41], and then this perfusion value is analyzed with time. In the latter case, signal processing tools are used to analyze evolution of blood perfusion with time. Signal processing studies performed on LDF signals may be of interest for signals obtained with LSCI ROI. A recent study proposed a method aiming at “denoising” perfusion signals computed from a ROI of LSCI images [32]. This processing work shows that the blood flow monitoring over moving skin surfaces can be possible with LSCI. However, except this study, to the best of our knowledge most of the LSCI processing works have been dedicated to *raw speckle images* or to *cerebral applications*, not to LSCI images for skin applications. Analyzing cerebral blood flow, some authors proposed a registered laser speckle contrast analysis method to remove the noise induced by respiration and/or heart beating [34]. They registered raw speckle images with a convolution kernel, normalized correlation metric and cubic B-spline interpolator and then constructed the contrast image [34]. A model based reconstruction for simultaneously image cerebral blood flow and de-oxygen hemoglobin distribution has also been proposed; for this purpose the authors used raw speckle images [33]. A processing scheme to extract temporal correlation parameters from the speckle contrast measured with a static or slow-evolving background has also been reported; the applications are performed on the cerebral hemodynamic response [48]. Some authors proposed a fractal characterization of LSCI images of the rat brain cortex [15]. Others used a box-counting approach (fractal analysis) of self-mixing speckle signal in velocity sensing [14]. In a more general context, a fractal-theory-based stochastic approach on speckle images has been reported to approximate the diffusion of light [11]. The authors mention a possible application to study the diffusion of light in human skin.

All these LSCI processes can be interesting. However, they are difficult to use in clinical routines because the user does not always have access to these *raw images* (the manufacturers often give the perfusion images only, not the raw data). Moreover, these processes have not been proposed for *skin* study. Linear and nonlinear signal processing studies performed on LDF signals could be applied on signals extracted from LSCI data (ROI perfusion values). Therefore, indices computed from LSCI images and reflecting the microvascular underlying mechanisms could possibly be as instructive as the ones computed from LDF signals. Furthermore, some of the one-dimensional studies performed on LDF signals could be extended in a two-dimensional plane to process LSCI perfusion images. As a result, potentially, much more processing capacities are available from LSCI perfusion images than from LDF signals. We, therefore, encourage the image and signal processing community to study LSCI perfusion images with the goal to extract skin physiological information needed by the clinicians.

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