Localization of transient signal high-values in laser Doppler flowmetry signals with an empirical mode decomposition

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The laser Doppler flowmetry (LDF) technique provides the monitoring of microvascular blood flow perfusion. However, LDF monitors based on fiber-optic transducers have the serious drawback of generating TRAnsient Signal High-values (TRASH) in signals. These TRASH correspond to artifacts for clinicians as they prevent interpretations of the signal when they are numerous. Moreover, TRASH exclude the possibility of direct signal processing and analyses. Therefore, in clinical routines, a human visual inspection of LDF signals is necessary to detect TRASH and to process the signals accordingly. This may be very time consuming. An algorithm able to localize TRASH *automatically* for their removal is therefore of interest. However, the development of such an algorithm is not an easy task as TRASH amplitude can be lower, higher, or in the same amplitude range as responses to stimuli such as post-occlusive hyperemia. The recently introduced empirical mode decomposition (EMD) has the advantage of splitting any kind of signal into fast and slow oscillations. Relying on these properties, the authors evaluate the possibility for EMD to localize TRASH automatically. For this purpose, LDF signals from 28 men of different ages are recorded at rest, during a vascular occlusion of 3 min, followed by a post-occlusive hyperemia. For each signal containing TRASH, the first intrinsic mode function obtained with the EMD is processed with a running window-based analysis in which a thresholding of the local maxima is carried out for the localization of TRASH. From the data, the use of a window width of 25 s is suggested. The results show effective and potential usefulness of this algorithm for an automatic localization of TRASH. Moreover, the method proposed has the advantage of being insensitive to the rapid increases of blood flow induced by post-occlusive hyperemia, which is of interest for clinicians. Because it is both local and fully data adaptive, EMD appears as an appealing processing technique for overcoming some of the limitations of the LDF. [DOI: 10.1118/1.3041168]

Key words: artifact, denoising, empirical mode decomposition, intrinsic mode function, laser Doppler flowmetry, microcirculation, motion, noise

I. INTRODUCTION

Microvascular blood flow can be monitored with the laser Doppler flowmetry (LDF) technique which, for skin, reflects perfusion in capillaries, arterioles, venules, and dermal vascular plexa.[1–3] LDF technique has led to many clinical research papers. However, as it is the case for many medical signals and images (see, for example, Refs. 4–6), LDF signals very often contain artifacts. Thus, LDF signals acquired with monitors based on fiber-optic transducers may present transient large peaks due to movements of the optical fibers, movements of the probe head relative to the tissue, or even from transient and very short physiological phenomena (tissue motions, displacement of arterial blood by a cuff compression at the beginning of a vascular occlusion stimulus).[7–13] These spikes, or TRAnsient Signal High-values (TRASH), correspond to artifacts for clinicians as they prevent interpretations of the signal when they are numerous. Moreover, they prevent direct signal processing and analyses. In order to overcome these drawbacks, LDF manufacturers tended to use small aperture fibers, with fewer modes.[7,8,10,14] Furthermore, in some LDF monitors, the manufacturer has implemented a spike rejection algorithm based on the analysis of the signal slope rate. However, the problem still persists.[12,15] Therefore, in clinical routines, a human visual inspection of LDF signals is necessary to localize TRASH and to process the signals accordingly. This may be very time consuming, particularly when measurements are made on people unable to remain still (babies, patients with tremors,…), or for long term recordings, situations for which no movement from the subject under study can be difficult to obtain. As a consequence, the development of an algorithm able to localize TRASH *automatically* for their removal has become of great interest. Nevertheless, the development of such an algorithm is not an easy task as TRASH can lead to signal increases that are lower, higher, or in the same amplitude range as those generated by responses to stimuli. Thus, post-occlusive hyperemia, which occurs after the removal of a vascular occlusion, generates a large and rapid blood flow increase that should not be removed because of its interest for clinicians.

A signal processing method based on two indices from information theory (Fisher information and Shannon entropy) has recently been proposed for TRASH localization.[16] Other approaches could be tested. However, as TRASH are not well characterized (their amplitude and duration differ), and since it is important to preserve the frequency content of the LDF signals for its physiological significance, commonly used de-noising tools such as filters or wavelets cannot be chosen. The goal of the present study is to analyze the potentialities of the recently proposed empirical mode decomposition (EMD) to localize TRASH. The EMD has the advantage of being a method which consists in splitting a signal into fast and slow oscillations with a local and fully data-driven approach. Its implementation is also very simple. Therefore, in order to evaluate the possibility for EMD to localize TRASH, 28 LDF signals recorded at rest, during a vascular occlusion, and during post-occlusive hyperemia are analyzed.

II. MEASUREMENT PROCEDURE AND SIGNAL PROCESSING METHOD

II.A. Measurement procedure

The LDF signals analyzed were recorded in 28 men of different ages (52.5 ± 10.4 years old) enrolled in a microcirculation study. All subjects gave their written informed consent to participate. Furthermore, the institutionally approved analysis (approval from the local ethical committee) was conducted in accordance with the Declaration of Helsinki. For the measurements, a laser Doppler optical fiber probe (PF408, Perimed, Stockholm, Sweden) connected to a laser Doppler flowmeter (Periflux PF5000, Perimed, Stockholm, Sweden) was positioned on the forearm (ventral face) of the subjects. As suggested by the manufacturer, the time constant

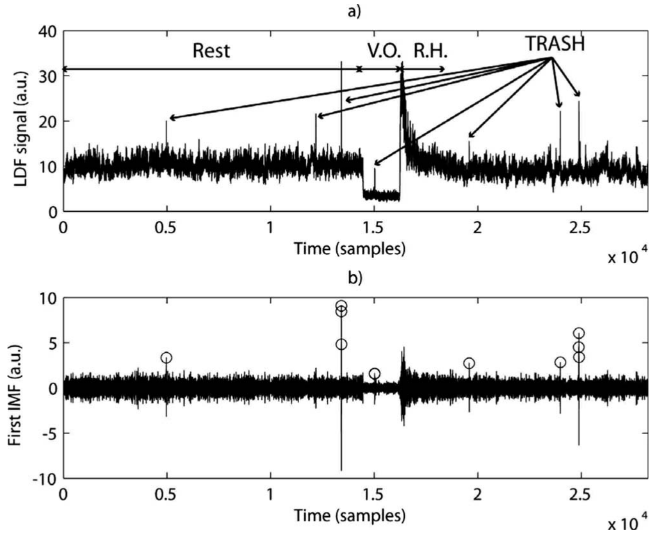

FIG. 1. (a) Skin LDF signal recorded during rest, vascular occlusion, and reactive hyperemia. V.O. stands for vascular occlusion. R.H. stands for reactive hyperemia. (b) First IMF of the LDF signal presented in (a). The "o" correspond to the TRASH detected by the EMD-based algorithm. The almost simultaneous circles correspond to several close signal samples which are considered as TRASH. For this algorithm, the window size is 25 s and the signal to noise ratio chosen for TRASH localization is 11.6 dB.

of the laser Doppler flowmeter was set to 0.2 s.[15] Skin blood flow revealed by LDF signals was assessed in arbitrary units (a.u.) and recorded on a computer via an analog-to-digital converter (Biopac System) with a sampling frequency of 20 Hz. The signals were then subsampled to 10 Hz for the EMD analysis. Recordings were performed with the subjects placed supine in a quiet room. After at least 10 min of acclimatization, skin blood flow was recorded for at least 20 min. Then, a cuff placed around the upper arm was inflated to 200 mmHg for 3 min (± 20 s) in order to perform a vascular occlusion. During this period, skin blood flow is stopped and the LDF signal therefore decreases to a very low level called the biological zero. The cuff was then released to obtain post-occlusive hyperemia [see Figs. 1(a) and 2(a)]. After their acquisition, the 28 LDF signals were examined by a human expert for an identification of TRASH.

II.B. Signal processing method

EMD has recently been introduced by Huang *et al.* for splitting a (possibly nonstationary) signal into fast and slow oscillations.[17] Given a signal $x(t)$, the effective algorithm of EMD can be summarized as the following main loop:[17]

(1) Identify all extrema of $x(t)$.
(2) Interpolate between minima to obtain an "envelope" $e\min(t)$. Same procedure for the maxima to obtain an "envelope" $e\max(t)$.
(3) Compute the average $m(t) = (e\min(t) + e\max(t))/2$.
(4) Extract the detail $d(t) = x(t) - m(t)$ and iterate at 2 on this detail $d(t)$ until the average, and thus the detail, is stabilized. The stabilized detail gives one IMF (the new IMF).

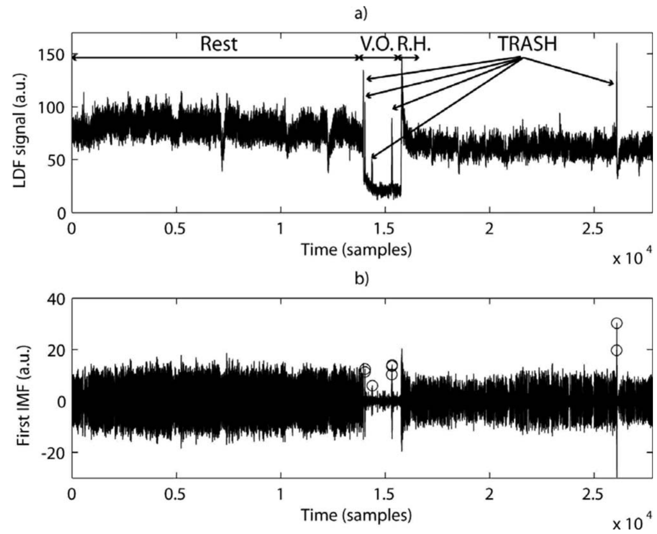

FIG. 2. (a) Same as Fig. 1(a). (b) Same as Fig. 1(b) but with a signal to noise ratio of 13 dB.

(5) Compute: new residual=current residual-new IMF (current residual=original signal at first).
(6) Iterate at 1 on the new residual (until stabilization of the next IMF), till the extracted IMF has only two extrema.

Eventually, the original signal $x(t)$ is decomposed through the main loop as[18]

$$x(t) = d_1(t) + m_1(t), \quad (1)$$

and the first residual $m_1(t)$ is itself decomposed as[18]

$$m_1(t) = d_2(t) + m_2(t), \quad (2)$$

so that

$$\begin{aligned} x(t) &= d_1(t) + m_1(t) = d_1(t) + d_2(t) + m_2(t) \\ &= \cdots \\ &= \sum_{k=1}^{K} d_k(t) + m_K(t). \end{aligned} \quad (3)$$

In our work, the stabilization criterion used (see step 4 above) is the one proposed by Rilling *et al.*[19]

As shown in Figs. 1(a) and 2(a), whatever TRASH amplitude and duration, TRASH and post-occlusive hyperemia correspond to the highest and fastest (compared to the LDF signal basal value) signal increases visible in the recordings. Moreover, EMD is based on the identification of local extrema of the time series. The first IMF thus contains the highest frequency fluctuations. Therefore, and based on the above-mentioned properties of TRASH and post-occlusive hyperemia, we propose to process each LDF signal containing TRASH with the EMD algorithm[19] and to extract the first IMF only. This first IMF should contain information enabling the differentiation between samples recorded at rest from samples corresponding to TRASH or post-occlusive hyperemia.

Once the first IMF is obtained, and in order to differentiate TRASH from post-occlusive hyperemia, we suggest the use of a running window applied on the IMF. In this window, we consider a local maximum as TRASH when its amplitude is higher than the product of a threshold by the mean value of the local maxima in the window (see Fig. 3). However, in order to be able to distinguish TRASH from post-occlusive hyperemia, the window size should be chosen so that its width is lower than the duration of post-occlusive hyperemia and higher than the duration of TRASH.

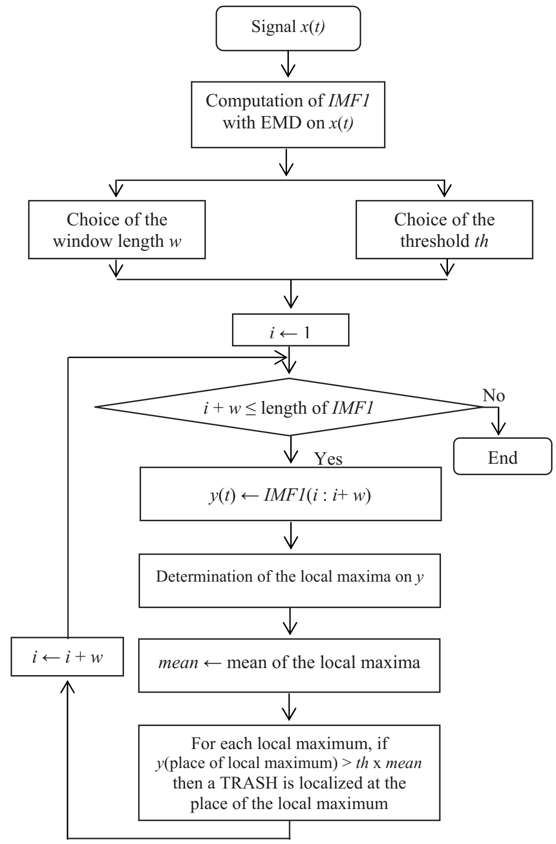

FIG. 3. Algorithm used to localize TRASH on LDF signals. ← means "takes the value of."

III. RESULTS AND DISCUSSION

On the 28 LDF signals recorded, the expert detected TRASH on 14 signals; the 14 other signals were considered as TRASH-free. Two LDF signals containing TRASH are presented in Figs. 1(a) and 2(a).

For a vascular occlusion of 3 min, a window size of 25 s (for application on the first IMF) satisfies the criteria of having a width lower than the duration of post-occlusive hyperemia and higher than the duration of TRASH. This width is therefore chosen in what follows. The results of the algorithm for the localization of TRASH in two LDF signals are presented in Figs. 1 and 2. From our results, we observe that the proposed algorithm can localize TRASH and can also be insensitive to the increase of blood flow generated by the release of a vascular occlusion of 3 min (post-occlusive hyperemia). This is the most difficult task when developing an algorithm for automatic TRASH localizations. In clinical routines, the specificity of the algorithm is more important than its sensitivity.

The choice of the threshold in the window-based analysis plays an important role in the results given by the algorithm. This threshold could be chosen from the signal to noise ratio in each window of the first IMF analysis. If the signal to noise ratio chosen is high (high threshold), less spikes are detected, and thus more false negative TRASH can be present. On the other hand, for a low value of the signal to noise ratio (low threshold), more artifacts can be located. Therefore, the threshold value has to be chosen as a compromise between the detection of false negative TRASH and false positive ones. This is illustrated in Fig. 1 where the signal to noise ratio chosen does not detect any false positive TRASH but leads to the detection of a false negative one. Once TRASH are determined, an indication mentioning that this part of the signal has a high probability of being noisy could be added. The clinicians could then choose to replace the part of the signal containing the spikes by TRASH-free data recorded in a period immediately prior to the noisy samples. We choose herein not to remove TRASH automatically after their localization because we are working with biomedical signals: in some cases, the removal of a part of the signal could also remove physiological information.

As mentioned previously, Fisher information and Shannon entropy have recently been proposed in TRASH detection.[16] The algorithm based on these two information theory indices has the advantage of being applicable on-line, contrary to the algorithm relying on EMD. However, computation of Fisher information and Shannon entropy necessitates setting six parameter values (three parameters for each index): the window size, the overlap, and the histogram resolution. Moreover, the choice of these parameter values can be a difficult task. On the contrary, the algorithm using EMD needs only two parameters to be set: the window length and the threshold value. It could therefore be easier to use for the clinicians. Furthermore, for the EMD-based algorithm, the window length has to be chosen relative to the vascular occlusion duration. Therefore, for a given occlusion duration (a given protocol), the window length has to be set only one time. What is more, in opposition to other TRASH algorithms that have been proposed in some patents, the algorithm proposed herein has the advantage of being simple in its implementation and does not require any frequency analysis of the photocurrent. Moreover, no characterization of TRASH (time duration) is necessary. Further work is now needed in order to validate the method in many more clinical situations.

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