AN INSTANTANEOUS FREQUENCY DISPERSION ESTIMATOR FOR DETECTING HIGH INTENSITY TRANSIENT SIGNALS IN HUMAN BLOOD FLOW

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ABSTRACT

This paper addresses the problem of automatic detection of High Intensity Transient Signals (HITS) in Doppler waveform. The aim of this work is to detect the passage of small particles in the human blood flow in order to prevent the formation of an arterial stenosis. Most existing methods are based on the short time Fourier transform of the Doppler ultrasound signal. We present an instantaneous frequency dispersion estimator for performing the automatic detection of HITS. After presenting the detection procedure, we also compare the detection results to that obtained by human experts. Finally, we comment the results and the limitations of this approach.

1 INTRODUCTION

Velocimetry using Doppler effect has known a considerable development in medicine since it allows for the non-invasive study of blood flow velocity in cardiac cavities as well as in very numerous vascular sites. In parallel to velocity changes, spectral analysis allows for the detection of power changes within the Doppler signal. The circulation of solid emboli (clotted blood, thrombi, atheroma, platelet aggregates, gaz....)[1] in the vascular system appears in the Doppler spectrum as a high intensity transient signal (HITS).

The ability to detect microemboli with ultrasounds has been underlined since the sixties[2] with an increased interest and activity renewal in this area in the last years[3]. Many postoperative accidents may be related to emboli, thus the continuous monitoring of patient with thromboembolic complications is of major interest. In the last years, manufacturers have developed commercial software systems that attempt to automatically detect, count and characterise (amplitude, duration) particles in the human blood. Although detailed algorithms are not always available, most of the detection methods take into account the relative increase of spectral energy of the Doppler signal, which is supposed to be large when a HITS occurs[4]. Nevertheless as presented in a recent study[5], audio and visual analysis of the Doppler signal by human experts remains the most reliable method to detect these events.

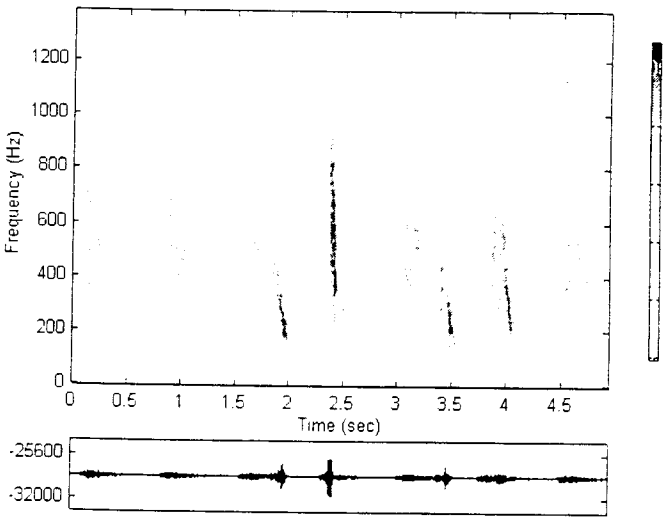

Figure 1: Time-Frequency displays of typical arterial Doppler signal. Four embolic signals are clearly visible within 3-6 cardiac cycle in Doppler spectrogram display, however the fourth was hardly audible.

We present in this article a new approach to analyse Doppler signal in order to detect the passage of microemboli in the human arterial blood. To evaluate the accuracy of this method, we compare the results of the detection obtained through our automatic detection system to those of six human experts.

2 METHOD AND MATERIAL

2.1 Description of the Method

The passage of a particle under the ultrasonic probe provides an abrupt variation of the amplitude of the signal, accompanied by a shrinkage of the Doppler spectrum within a dominant frequency (c.f. figure 1). We have

made the assumption that the Doppler signal can be considered as a narrow band signal when a embolus occurs. The Doppler signal $s(n)$ was modelled as the real part of a complex signal $z(n)$[6] :

$$z(n) = s(n) + jH[s(n)]$$
$$s(n) = \mathrm{Re}\{z(n)\}$$

where $H[\ ]$ was the discrete-time Hilbert transform defined by :

$$H[s(n)] = \sum_{-\infty}^{+\infty} \frac{2s(n-m)}{m\pi}$$

Writing the analytic signal z(n) in the polar form :

$$z(n) = a(n)e^{j\phi(n)}$$

where $a(n)$ and $\varphi(n)$ are the discrete magnitude and phase.

We define the discrete-time instantaneous frequency as the backward difference of the phase:

$$f_i(n) = \frac{fcch}{2\pi} \cdot [\phi(n) - \phi(n-1)]_{\mathrm{mod}\,2\pi}$$

and the discrete-time envelope:

$$a(n) = \sqrt{s(n)^2 + H[s(n)]^2}$$

This instantaneous frequency estimator is sensitive to the signal bandwidth : the larger bandwidth, the stronger the estimated variations (and vice versa). Hypothesing that HITS are narrow band signals, the fluctuations of the instantaneous frequency estimation shall be weaker when a HITS occurs than for the rest of the Doppler signal (c.f. figure 2). Moreover, emboli providing high intensity signals, the envelope of the Doppler signal will be increased. Thereby we calculate the instantaneous frequency and envelope dispersions.

The first step of the detection procedure consists, within a 128-point sliding window, in the estimation of the instantaneous standard deviations ($\sigma_a(n)$ and $\sigma_{f_i}(n)$) of the instantaneous envelope and frequency by the instantaneous estimator[7] described in the figure 3.

The instantaneous standart deviation of the envelope then was normalised by the dispersion of the signal when no embolus occurs and when the instantaneous frequency deviation is high (arbitrarily defined > 500). In this case, the signal no longer can be considered compatible with the narrow band hypothesis.

Emboli will provide strong deviations of amplitude and weak instantaneous frequency dispersions, thus the instantaneous ratio of these two magnitudes is higher for emboli that for the rest of the Doppler Sound :

$$\rho(n) = 20 \cdot \log_{10}\left(\frac{\sigma_a(n)}{\sigma_{f_i}(n)} \cdot fech\right)$$

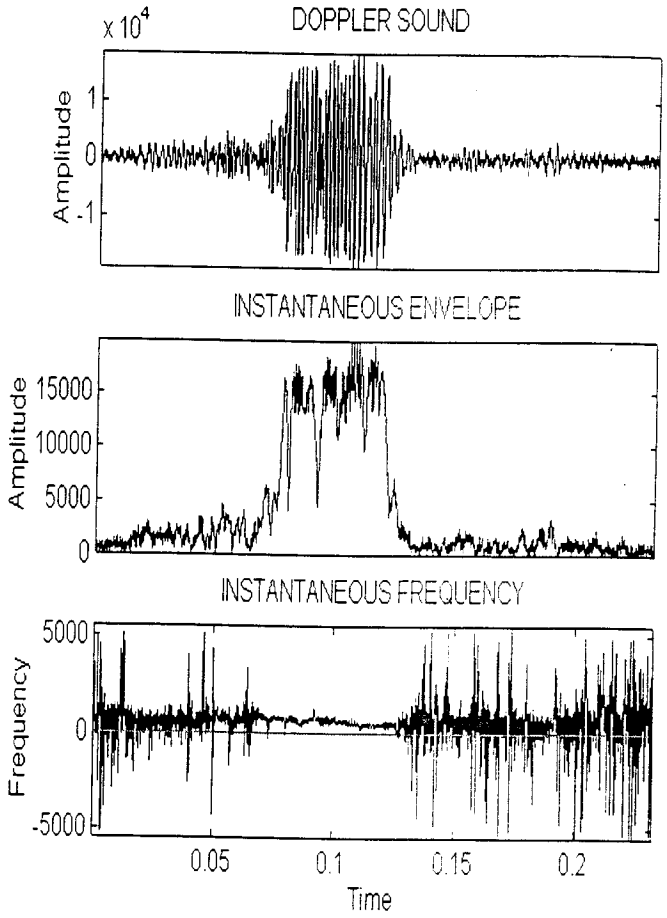

Figure 2: Doppler sound, instantaneous envelope and instantaneous frequency of the second HITS from the figure 1. This figure illustrates the narrow band hypothesis when an embolus occurs

(where $fech$ is the sampling frequency).

Finally, we retained only instants where $\rho(n)$ is superior to a fixed threshold ($S_{detection}$) experimentally defined. To avoid multiple detections for the same event, all consecutive detections occurring within 110 samples (~10 ms) from the previous detection were considered to be related to a single episode. If two consecutive detections were separated by more than this particular interval, the second event was considered as a new one.

2.2 Material and Doppler Signals

Signals have been collected on the postero-tibial artery using a continuous 4 MHz ultrasound Doppler device (Angiodop 481, DMS, France) during invasive radiological procedures. Collected embolic signals were consecutive to the mobilisation of the radiological probe in the artery, or to the injection of radiological contrast product or saline. The clinical results of this study have been reported elsewhere[8]. From Doppler recordings,

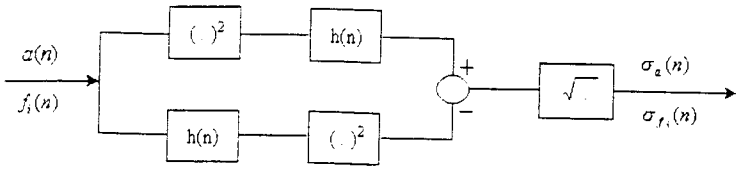

Figure 3: Shematic representation of the instantaneous standard deviation estimation. $h(n)$ is the impulse response of an average filter. $h(n)$ must verify the condition $\sum_{-\infty}^{+\infty} h(n) = 1$

we established two databases. The first was constituted from 560 HITS and has allowed us to study the embolic phenomenon. We have tested the detection procedure with this database for different values of $S_{detection}$. The value that provided false-positive = false-negative was than chosen to compare results of the automatic detection with those of human experts in a second experiment. The second database came from 12 different other patients. Thereafter we confronted detection of our automatic technique to those coming from six other humans experts.

3 RESULTS

The threshold chosen that realised $fp = fn$ in the first database was 45.9. With this value we obtained 85.4% of good detections, 14.6% of no detections and 14.5% of false detections (c.f. figure 4). Thereby we used this value to apply our automatic detection technique on the second database.

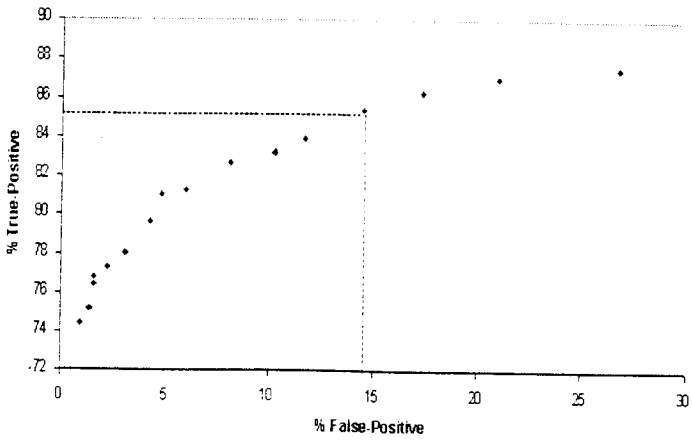

Figure 4: Percentages of true-positive as a function of false-positive for different values of the threshold

On the recordings of the second database, humans experts (1 to 6) reported 140, 176, 155, 161, 161, 146

%	O1	O2	O3	O4	O5	O6
tp	87.9	79.5	89.1	83.2	81.4	91.1
fp	19.1	7.9	9.2	11.8	13.8	13.2
fn	12.1	20.5	10.9	16.8	18.6	8.9

Table 1: Percentages of true-positive, false-positive and false-negative obtained by the proposed method for each observer O1-O6

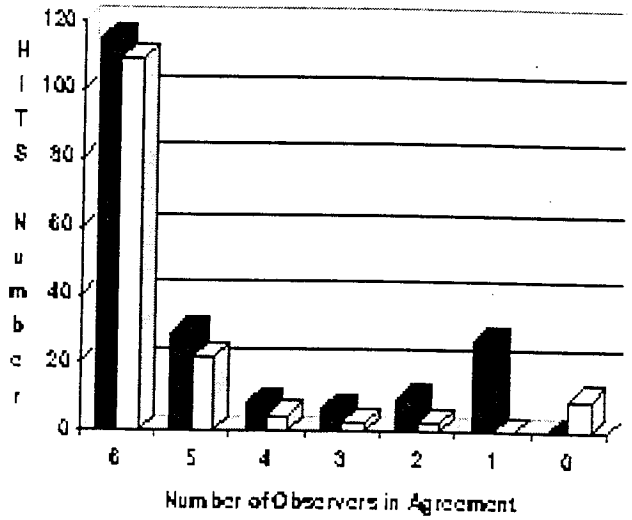

Figure 5: Number of true-positive automatic detections (gray bars) and number of events detected by the human observers (black bars) as a function of the number of observers in agreement.

events respectively, corresponding to 197 different events since 115 events where found by all observers, 29 by 5 observers, 9 by 4 observers, 7 by 3 observers, 10 by 2 observers and 27 events by 1 observer. With the automatic method we obtained 152 detected events. Table 1 resumes the percentages of true-positive (tp), false-positive (fp) and false-negative obtained by the automated method for each observers. On average, 85.4% of true-positive was obtained corresponding to 12.5% of fase-positve.These results are consistent with those provided by the experimental determination of the detection threshold in the first experiment.

As presented in figure 5, 94.8% of 115 HITS heard by all observers have been detected by the automatic method. This proportion decreases as the number of observer-in-agreement decreases. If we consider only significant HITS heard by at least 4 human experts (" human gold standart "), then the automatic method provides 88.9% of good detections for 10.5% of false detections (c.f. figure 6).

We have performed a preliminary experience in 4 patients (2h45 of recording) where the signals have been

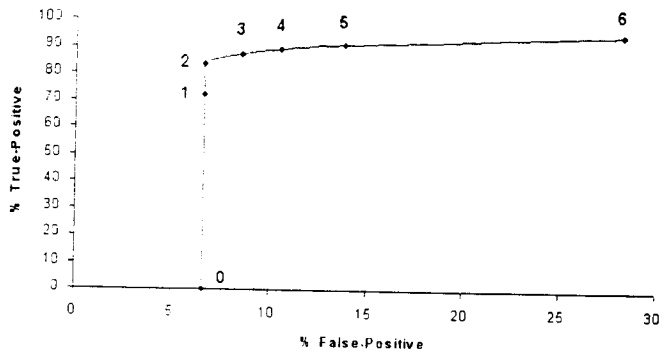

Figure 6: Percentages of true-positive as a function of false-negative for different number of human-experts-in-agreement (HEIA): 0- at least 0 HEIA, 1- at least one HEIA, 2- at least two HEIA, 3- at least threeHEIA, 4- at least four HEIA, 5- at least five HEIA, 6- at least six HEIA.

subdivided into periods of 1s to localise the moments at which signals occurred as suggested in [5]. On these 2h45 recordings, the automated method has found 35 HITS (37 detected by the human experts) and 68 signals in excess. Among these 68 extra detection, 22 are "true" false-positive. 21 events correspond to artifact. And after a second human analysis of these 68 events, 25 signals were reported as possible HITS. This technique of course does not provide specificity results but a significant difference is found between observers which should be the gold standard. Only an in vitro study with visual control of the embolic passage would allow for the analysis of specificity of the detection.

4 CONCLUSION

Our approach for the automatic detection of peripheral arterial HITS provides satisfactory results on both sensibility and positive predictive values compared to human expert detection.

In our concept the automatic detection of embolic signals should be performed in the same maner than in 24H EKG holters. This means that the sensitivity of the proceeding should be high and post proceeding analysis of the detected events should be performed by human experts to differentiate HITS from artifacts. Thereafter we need a good sensitivity with reasonable specificity. Although a low specificity would require time consuming human analysis in this concept a high sensitivity is to be searched. The fact that in the post proceeding human analysis, some of the automatically detected events are probably to be considered as true HITS that where not detected by human expert in the 2h45 recording is consistent with this approach.

In the present study we were not interested in the HITS discrimination from artifact. Nevertheless, the artefacts which occur under real monitoring conditions are a real problem in HITS detection. Further studies are needed after this approach to improve the HITS discrimination from artifact. Complementary study in a larger population should be done to increase the definition of the threshold used in the detection process.

5 REFERENCES

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