Multiscale Analysis of Blood Pressure Signals

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We describe the multiresolution wavelet analysis of blood pressure waves in vasovagal syncope affected patients compared with healthy people, using Haar and Gaussian bases. A comparison between scale-dependent and scale-independent measures discriminating the two classes of subjects is made. What emerges is a sort of equivalence between these two methodological approaches, that is both methods reach the same statistical significance of separation between the two classes.

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In recent years biological time series have been considered in the more general framework of fractal functions. Accordingly, the analysis tools commonly used for fractal functions, have been applied to study physiological time series, see e.g. [1]. A major approach to such problems is based on the wavelet transform, a technique which has proved to be well suited for characterizing the scaling properties of fractal objects even in presence of low-frequency trends [2].

In particular, the regulation of the cardiac rhythm, has been recently investigated in two very interesting papers aiming at providing means of diagnosis of heart disease. The interbeat interval records for healthy and sick subjects have been studied by wavelet analysis, which can appropriately treat the non-stationarity of these signals. In Ref. [3] a scale dependent measure, the root-mean square of the wavelet coefficients $\sigma_w(s)$ at a particular scale $s$, has shown to be able to sharply discriminate between healthy and sick subjects. In Ref. [4] it was observed that scale-dependent measures may reflect characteristics specific to the subject or to the choice of the wavelet basis; a scale-independent measure extracting the exponents characterizing the scaling of the partition function of wavelet coefficients was then proposed, and its performance in detecting heart disease was excellent. The scaling exponents were already studied in Ref. [3] for the second wavelet moments while in Ref. [4] they are calculated for arbitrary moments. It seems likely to us that the approaches based on scale-dependent measures and that based on scale-independent ones should be considered as qualitatively equivalent. Indeed some pathological conditions may alter the cardiac dynamics at a specific scale or range of scales, while the scaling behaviour of the dynamics of cardiac rhythm regulation should be universal for subjects belonging to the same class. An important problem is how the choice of the wavelet basis influences the results of the analysis. Moreover it is interesting to check whether the same kind of analysis can be used to study other physiological time series and pathologies.

In this work we study the temporal series of the systolic blood pressure waves maxima in nine healthy subjects and ten subjects showing a pathology known as vasovagal syncope. We perform a wavelet analysis of these time series and consider both the scale-dependent and the scale-independent measures above described. To our knowledge this is the first time wavelets are used to study blood pressure waves signals. We performed the analysis using two different wavelet bases, namely the Haar basis and the third derivative of the Gaussian one (TDG). The main difference between these two bases is that the former is able to remove only zero order trends, while the latter is insensible to higher polynomial trends. We find that the Haar basis is, with respect to the data set at hand, well suited for scale-dependent measures i.e. measures of $\sigma_w(s)$. Indeed using these wavelets we find an evident separation among healthy and sick subjects at a particular scale $s = 32$: this separation is missing when the TDG is used. On the other hand, using the TDG leads to a separation with respect to scaling exponents measures which is quite less significant when the Haar basis is used. Interestingly we found that the statistical confidence of separation in the scale-dependent
parameter (obtained using Haar wavelets) is very close to that obtained by the scale-independent parameter i.e. the scaling exponent (using the TDG). Since both methods have reached the same degree of separation between the two classes, it remains to be understood whether this coincides with the intrinsic degree of separability of the data set here considered.

Vasovagal syncope is a sudden, rapid and reversing loss of consciousness, due to a reduction of cerebral blood flow attributable to a dysfunction of the cardiovascular control, induced by that part of the Autonomic Nervous System (ANS) that regulates the arterial pressure. In normal conditions the arterial pressure is maintained at a constant level by the existence of a negative feed-back mechanism localised in some nervous centres of the brainstem. As a consequence of a blood pressure variation, the ANS is able to restore the haemodynamic situation acting on heart and vessels, by means of two efferent pathways, the vasovagal and sympathetic one, the former acting in the sense of a reduction of the arterial pressure, the latter in the opposite sense. Vasovagal syncope consists of an abrupt fall of blood pressure corresponding to an acute haemodynamic reaction produced by a sudden change in the activity of the ANS (an excessive enhancement of vasovagal outflow or a sudden decrease of sympathetic activity).

Vasovagal syncope is a quite common clinical problem and in the 50% of patients it is non diagnosed, being labelled as syncope of unknown origin, i.e. not necessarily connected to a dysfunction of the ANS action. Anyway, a rough diagnosis of vasovagal syncope is practicable with the help of the head-up tilt test (HUT). During this test the patient, positioned on a self-moving table, after an initial rest period in horizontal position, is suddenly brought in vertical position. In such a way the ANS registers a sudden stimulus of reduction of arterial pressure due to the shift of blood volume to inferior limbs. A badly regulated response to this stimulus can induce syncope behaviour.

According to some authors, the positiveness of HUT means an individual predisposition toward vasovagal syncope. This statement does not find a general agreement because of the low reproducibility of the test in the same patient and the extreme variability of the sensitivity in most of the clinical studies. For this reason a long and careful clinical observation period is needed to establish with a certain reliability whether the patient is affected by this syndrome. What we want to stress here is that, from a clinical standpoint, there is not a neat way of discriminating between healthy and syncope-affected subjects, while, in the case of heart disease, studied in [3,4], there is always a very clear clinical picture. For this reason in last years a large piece of work has been devoted to the investigation of signal patterns that could characterise syncope-affected patients. This has been done especially by means of Fourier analyses of arterial pressure and heart rate which have not shown to be successful for this purpose.

The temporal behaviour of blood pressure is the most clinically relevant aspect to study vasovagal syncope since it is the result of the combined activity of ANS on heart and vessels. Therefore we extract blood pressure wave maxima from a recording period twenty minutes long (which is the better we can do for technical reasons). During this time the following biological signals of the subject are recorded: E.C.G. (lead D-II), E.E.G., the thoracic breath, the arterial pressure (by means of a system finapres Ohmeda 2300 Eglewood co. USA, measuring from the second finger of the left hand).

We denote \( \{P_i\} \) the time series of systolic pressure maxima. The coefficients of the discrete wavelet transform at scale \( s \) are given by:

\[
W_s(n) = s^{-1} \sum_{i=1}^{M} P_i \psi((i - n)/s),
\]

where \( \psi \) is the generating wavelet, \( M \) is the number of points in the time series (we have \( M = 2^{10} \)), \( n \) is the point for which the coefficient is calculated. The scale-dependent measure proposed in [3] corresponds to evaluate the root-mean square of wavelet coefficients at fixed scales. The scale-independent measure deals with the sums of the moments of the wavelets coefficients

\[
Z_q(s) = \sum_n |W_s(n)|^q,
\]

where the sum is only over the maxima of \( |W_s| \). One can show that \( Z_q \) scales as:

\[
Z_q(s) \sim s^{\tau(q)}.
\]

The exponents \( \tau(q) \), especially for \( q = 2 \) and \( q = 5 \), were found to provide a robust degree of separation in the case of heart disease diagnosis.

Firstly we discuss the results we obtained on the data set here considered by the evaluation of the r.m.s. of wavelet coefficients. In Fig. 1(a) the r.m.s. of the Haar wavelets coefficients are plotted versus the scale, for both sick and healthy.
Ref. [15] shows that in the case of diverse heart pathologies, scale-dependent measures, namely measures of two kinds of measures are going in the same direction rather than excluding each other. A very careful analysis in Haar wavelets at a given scale, while the TDG seems insensible to the single scale features. It follows that these time series with respect to the Haar basis. On the other hand the same degree of separation is obtained by both Haar wavelets and the TDG basis. A measure of the exponents \( \tau(q) \) can then be obtained through log-log plots of \( Z_q(s) \) versus \( s \). In the case of the TDG, the log-log plots of \( Z_q(s) \) versus \( s \) showed a neat scaling behaviour: in Fig. 2 the \( q = 1 \) case, the most significant with our data, is shown. In the case of Haar wavelets, the log-log plots show some curvature (see Fig. 2), but calculating linear correlation coefficients we discover that it still makes sense to evaluate \( \tau(q = 1) \) exponents. For the moment let’s refer to the TDG case. We found that the exponent \( \tau(q = 1) \) acts as a discriminating parameter between healthy and sick subjects, while exponents for the other values of \( q \) did not succeed in obtaining equally convincing results. Healthy subjects have lower \( \tau(q = 1) \) values than syncope affected ones (see. Fig. 3). By WMW test, the probability that the values of the exponents found for the two classes of subjects, healthy and sick, were sampled from the same continuous distribution was estimated \( 4.5 \times 10^{-3} \), a level of significance very close to the one found in the case of the scale-dependent measure. On the other hand, considering the \( \tau(q = 1) \) as computed in the Haar basis, we find that the latter probability value grows of about one order of magnitude reaching a value of \( 2.1 \times 10^{-2} \).

In Fig. 3 we have shown the points corresponding to the 19 subjects under consideration in the \( \sigma_w - \tau \) plane, where the coordinates correspond to the measured quantities \( \sigma_w(32) \) (by Haar wavelets) and \( \tau(q = 1) \) (by the TDG basis). It is evident that the two measures separate, at the same degree, the two classes.

We observe that it is reasonable that the Gaussian basis is more effective in detecting the scaling behaviour of these time series with respect to the Haar basis. On the other hand the same degree of separation is obtained by Haar wavelets at a given scale, while the TDG seems insensible to the single scale features. It follows that these two kinds of measures are going in the same direction rather than excluding each other. A very careful analysis in Ref. [15] shows that in the case of diverse heart pathologies, scale-dependent measures, namely measures of \( \sigma_w(s) \) at a particular scale \( s \), outperform measures of scaling exponents. Due to the size of our data set, we may encounter problems in reproducing the kind of analysis performed in Ref. [14], but we look forward to investigate this aspect. In Ref [13] is also stressed that baroflex modulations of sympathetic and parasympathetic tone lie in a frequency range which corresponds to the scale \( s = 32 \) which is, also for us, the best discriminating between controls and positives.

We are, at the moment, not able to provide the physiological explanation of the phenomena here described. However these results might be useful to get a better understanding of the very complicated vasovagal syncope pathology.

Some conclusions are in order. We analysed by wavelets blood pressure signals from healthy subjects and subjects positive to vasovagal syncope pathology. We evaluated two quantities, one depending on a fixed scale and a scaling exponent, which have been recently proposed as diagnosis tools for heart disease. We have shown that both the measures succeed in separating the two classes within the same degree of significance. We are working to have longer records and an enlarged number of positives and controls so as to refine our analysis. At the moment we are aware to be far from being able to propose an alternative diagnostic tool. This would be very useful in consideration of the particular difficulty that the clinical diagnosis of vasovagal syncope still presents.

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Fig. 1 - Standard deviations of the wavelet coefficients of the systolic pressure in syncope-affected patients (positives) and healthy people (controls) drawn both in Haar basis (a) and Gaussian basis (b). Note the evident separation among positives and controls at $s = 32$ in (a). This separation is completely lost in (b). We believe that the discrimination pattern is not as sharply evident as in Ref. [3] due to the restrict temporal extension of our data set. We use different $\sigma_w$ ranges in (a) and (b) just in order to have a best visual impact of figures.
Fig. 2 - Log-log plots of $Z_1(s)$ vs. $s$ drawn in Haar basis and in Gaussian basis for a subject. Analogous plots have been obtained for the other subjects we have examined. The scaling behaviour is evident only in Gaussian basis, while the points from the Haar basis are not as well linearly fitted.
Fig. 3 - $\sigma_{w}(32)-\tau(1)$ plot i.e. the Haar wavelet coefficient fluctuation at the scale $s = 32$ vs. the scaling exponent of Eq. (3) in Gaussian basis. • is referred to syncope-affected patients, ◦ is referred to healthy subjects. Projecting the points laying in the $\sigma - \tau$ plane on $\sigma$ and $\tau$ axes we obtain two separation patterns between positives and controls which are quite similar from a statistical point of view (see the WMW analysis in the text).