The Frequency Changes in Electrograms during Ischemia Experiments – Analysis by Matching Pursuit Decomposition

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Abstract

The aim of this study was to analyse frequency components in electrograms (EGs) recorded from surface of isolated guinea pig hearts perfused according to Langendorff. Time-frequency analysis is based on algorithms Matching Pursuit and Wigner-Ville Distribution and its combination showing the energy density of the signal. The presented algorithms were tested on a set of electrograms, recorded during ischemia followed by reperfusion. The frequency components changed markedly during global ischemia experiments.

1. Introduction

The analysis of electrograms (EGs) represents an important tool for diagnosing various heart diseases, which are the main cause of mortality in developed countries. The importance of the automatic measurement or detection of significant abnormalities in a signal grows with the growing need for rapid assessment of electrocardiographic data. These include in particular the detection of cardiac ischemia that causes myocardial infarction which largely contributes to mortality worldwide. In case of ischemia the severity of tissue damage (that can lead to cardiac dysfunction and acute heart failure) is determined primarily by the time. Therefore, early detection of ischemia is of such a great significance.

There are many different approaches for ischemia detection. In clinical practice, ischemia can be assessed most frequently by monitoring of morphological parameters of ECG (such as ST60 level and/or T wave amplitude, etc). Many authors studied the effects of frequency changes accompanying ischemia on ECG signal by Fourier transform. Some approaches are focused on detection of the changes in ECG in time and frequency domain simultaneously by Wavelet transform [1] or Matching Pursuit algorithm [2,3,4].

However, the delay between the occurrence of ischemia and its detection is relatively long. Time-frequency analysis methods using Matching Pursuit achieves excellent accuracy of detection, and in a short time.

2. Methods

The frequency changes in EG signal were studied during global ischemia experiments on isolated hearts perfused according to Langendorff. Three orthogonal EG leads were followed under control conditions and during ischemia and reperfusion periods.

The EG signals were analysed by Matching Pursuit (MP) decomposition [2]. This method decomposes a signal into an optimal linear expansion of waveforms, which are functions previously defined in a dictionary, and thus extends capability of traditional tools. The MP method is applied to study changes of energy of EG signal frequency components during all experimental periods. The EDs of the relative frequency of waveforms resulting from MP were computed to show frequency details for each experimental period.

2.1. Experiment

Seven guinea pig hearts were involved in this study. After the heart isolation, the heart was fixed to perfusion setup by the stump of aorta and then placed into thermostat-controlled bath (37°C) filled with Krebs-Henseleit (K-H) solution. The solution was continuously oxygenated with 95% O_2 and 5% CO_2. The heart was then perfused with the same solution at the constant perfusion pressure for 25-30 minutes (control period). After that, global ischemia was induced for 15 minutes and then the perfusion was restored for another 15 minutes. During all periods (control, ischemia, and reperfusion) simultaneous touch-free recording of the electrogram was performed.

The EG signals from orthogonal leads were simultaneously recorded from Ag-AgCl electrodes positioned on the inner surface of the bath during all experimental periods (control, ischemia, reperfusion). The signals were digitized by a 12-bit AD converter at 2 kHz sampling rate using a data acquisition multifunction card PCI-6111E (National Instruments, USA). The digital signal was stored on a hard disk for further off-line processing [5].

In the context of signal preprocessing there has been no signal filtering. The conditions laid down for working wave detector R: the size of maximum amplitude of the waves detected by a wave detector R must be within 60 - 140% of the size of the previous R wave. Introducing a lower limit has suppressed false designation of T waves, which in some measured signals are approximately half deflection of waves R. Impulse noise detection was eliminated by reducing the upper limit. Other detection preprocessing is to highlight QRS by exponentiation of the signal. Total length indexed EG cycle corresponds to 120% of the length of the RR interval (overlap is due to varying QT, etc.), with the division at 40% RR before the detected R wave (start indexing) and 80% for the RR (end of indexation). The EG signals were analyzed by Matching Pursuit (MP) decomposition. Below is a table of the success of the detector with the values of sensitivity and positive predictivity.

Table 1. Sensitivity and positive predictivity of the detector.

	R waves	FN	FP	Se [%]	P⁺ [%]
n. 1	4563	0	0	100,00	100,00
n. 2	4810	0	1	100,00	99,98
n. 3	5058	0	0	100,00	100,00
n. 4	5359	2	0	99,96	100,00
n. 5	4683	32	0	99,32	100,00
n. 6	5778	2	8	99,97	99,86
n. 7	5014	1	3	99,98	99,94
sensitivity and positive predictivity				**99,90**	**99,97**

2.2. Matching Pursuit Decomposition

Matching Pursuit is an algorithm of adaptive approximation of the signal using redundant dictionary of function. The resulting signal approximation does not coincide exactly with the original signal, but it approximates using a few selected functions of dictionary.

For the time-frequency analysis, Gabor dictionary functions were used, which are the Gaussian envelope modulating sinusoidal oscillations. Gaussian function can be expressed as

$$g_\gamma(t) = K(\gamma)e^{-\pi\left(\frac{t-u}{s}\right)^2}\cos(\omega(t-u)+\varphi),$$

where s is the scale parameter, u represents a shift, frequency ω and phase φ. By this equation we are able to parametrically describe a wide variety of wavelets (functions). Matching Pursuit algorithm finds suboptimal solutions through successive iterations. The finding of approximation is based on the principle that the unknown signal x can be expressed by the sum of known valuated functions which have been selected from the dictionary. If the dictionary is composed of orthonormal wavelets basis, then the coefficients (of valuation) are given only by the inner product of the signal with the functions from dictionary.

At the beginning of the algorithm is the residual of the signal itself input signal x. In each iteration function (atom) from a dictionary is chosen that best approximates the residue of the signal, i.e. such a Gabors atom, which maximizes the inner product of signal and atom. The residue is then gradually reduced by subtraction outcome of the previous iteration. By gradual composing of selected atoms is received signal which with increasing M (number of used wavelets) converges to the original signal x

$$x \approx \sum_{n=0}^{M-1}\langle R^n x, g_{\gamma_n}\rangle g_{\gamma_n}.$$

Decomposition of EG signal is shown in Figure 1. The termination criterion of algorithm was given as 30 iterations. Therefore, a total of 30 Gabor atoms was selected from the dictionary for the approximation of the original signal.

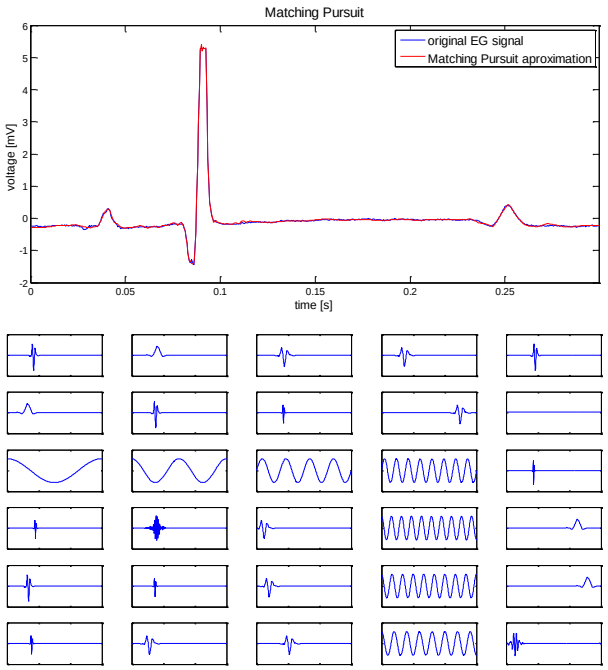

Figure 1. Matching Pursuit decomposition of ECG signals. Top: EG cycle recorded during control period (red) and its approximation (blue); Bottom: Chosen Gabor atoms that gives approximation of EG signal figured on top.

2.3. Wigner-Ville Distribution

For the analysis of the signal based on conformity assessment, the most important criteria are inner product, orthogonality, frequency, and phase. The basic

representation of the spectrum of the short segment of the signal is spectrogram computed by Short-Time Fourier Transform (STFT). Functionally similar representation is Wigner-Wille Distribution (WVD). It does not suffer on leakage effect (as STFT does) and it is one of the most fundamental approach in time-frequency representation of the signal. This method is based on the equation of autocorrelation

$R_{xx}(\tau) = \int_{-\infty}^{\infty} x(t+\tau)x^*(t)dt = \int_{-\infty}^{\infty} x(t)x^*(t-\tau)dt,$

where τ is time delay or time shift. Using small modifications we can get form of the equation

$$R_{xx}(\tau) = \int_{-\infty}^{\infty} x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})dt.$$

And since we can write square root of Fourier transform as autocorrelation of the signal (due Wiener-Kninchin teorem) we get form

$$|\mathcal{F}(x)|^2 = \mathcal{F}\left(\int_{-\infty}^{\infty} x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})dt\right).$$

By removing the middle integral corresponding to the integration over time, we get a time-dependent spectral density as a 2-dimensional function in th shape

$$W(t,f) = \int_{-\infty}^{\infty} e^{-i2\pi f\tau}\, x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)d\tau.$$

This is Wiegner-Ville transform of the signal x. The Wigner-Ville transform is one of fundamental approach in square time-frequency representations due to its mathematical elegance and some basic features. However, also in this method we can see a common problem – distribution is not always zero in time when the value of the signal is zero. In other words, the distribution is not always zero for unrepresented frequencies in the spectrum. This is called cross-terms.

Cross-term can be suppressed, but without any prior knowledge of the signal it is not possible to suppress only cross-terms without damage of auto-terms which include useful information of the signal. The solution may be combination of Matching Pursuit approximation and Wigner-Ville distribution.

2.3 Energy density of the signal (MPWVD)

By application Wigner-Villa's distribution directly to the equation we get

$$(x) \approx W\left(\sum_{n=0}^{M-1} a_n g_{\gamma_n}\right),$$

which is equivalent to

$$\sum_{n=0}^{M-1} {a_n}^2 W\left(g_{\gamma_n}\right) + \sum_{n=0}^{M-1}\sum_{k=1,k\neq n}^{M-1} a_n a_k W(g_{\gamma_n} g_{\gamma_k}),$$

where $a_n = \langle R^n x, g_{\gamma_n}\rangle$.

The double sum includes cross-terms. Using linear expansion this double sum can be omitted and express the time-frequency representation of the signal energy density (including only auto-terms)

$$\varepsilon x = \sum_{n=0}^{M-1} \left|\langle R^n x, g_{\gamma_n}\rangle\right|^2 W g_{\gamma_n}.$$

This method is applied to all data and electrograms are analyzed on the basis of changes in the time-frequency maps during experimental periods (stabilization, ischemia, and reperfusion).

Thanks to changes in the shape of EG signal in relation to elevation of ST segment accompanying ischemia different atoms were used to decompose the EG signal, which is reflected in the different appearance of the main energy cluster of EG signal in time-frequency map. In the map presenting ischemia you can see a large representation of low frequencies, which reflects the use of most atoms of low frequencies. By comparing the time-frequency maps of stabilization and ischemia can be easily determine which map corresponds ischemia. During reperfusion, we see an almost identical time-frequency map, reflecting the fact that there is a return to shape during stabilization. See Figure 2.

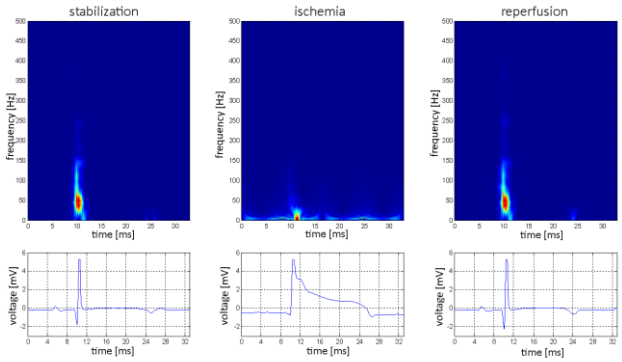

Figure 2. Matching Pursuit decomposition of EG signals during experimental periods (stabilization, ischemia, reperfusion) Top: Time-frequency MP maps in frequency range of 0Hz-500Hz. Colour legend: from blue to red – low to high energy areas. Bottom: EG cycles recorded during experimental periods.

2.4. Ischemia detection

It has been calculated more than 300 time-frequency maps of stabilization and ischemia for each measurement. The average time-frequency map representing stabilization and ischemia was created from each such file. In the same manner the average time-frequency map for reperfusion was calculated. Thus was obtained reference models for the measurement phase.

For the analysis of time-frequency maps were used energy distribution (ED). ED show energy of atoms with respect to frequency in the time-frequency map. By this is obtained overview how much energy belongs to specific frequency.

If we plot EDs for the various phases of the measurement, it can be seen that during the stabilization the most significant frequency components are 40-50 Hz.

During ischemia occur frequency changes manifested by the presence of components with major energy at frequencies of 2-20 Hz. During reperfusion there are gradual changes back until a certain period will stabilize at values very close to the stabilization phase. For details see figure 3.

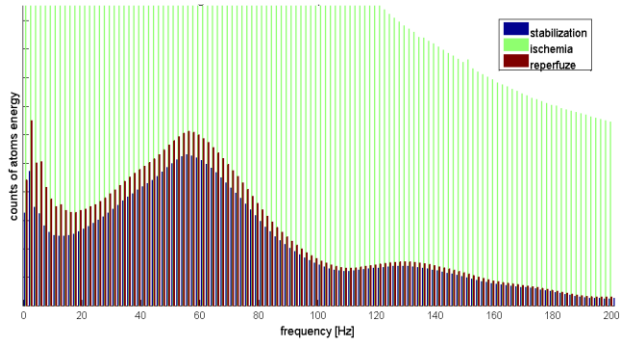

Figure 3. Energy distribution of all Gabor atoms used for MP decomposion of EG (in frequency band 0-200 Hz) for all experimental periods (stabilization, ischemia, reperfusion).

On the basis of these results (observable in all measurements) was created ischemia detector. The detector works online, based on detection of the RR interval a time-frequency map (based on MPWVD) was calculated for each EG cycle and then its ED. Ischemia is detected by comparing the current ED with the reference ED of stabilization phase. Reference ED model is created online and adaptively refinement. There is no priori knowledge of the signal necessary, and yet the reference model is created for the signal to measure providing in higher speed and reliability of detection.

3. Results

Detection of ischemia was in all cases of measurement successful and very fast, in most cases, ischemia was detected at the time of around 2 minutes, while in this time is not yet obvious from the waveform.

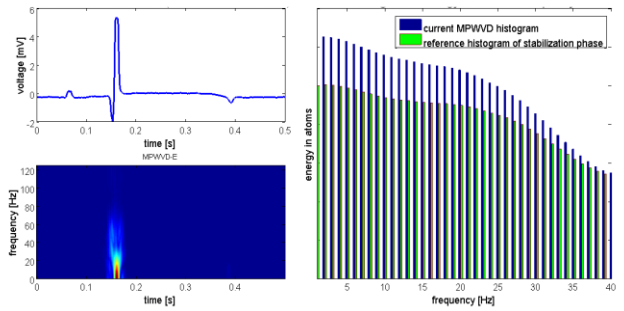

Figure 4. Top left: EG signal from the 5th minute of ischemia; Bottom left: MP decomposition of EG signal showed upper in frequency band (0-120 Hz); Right: Energy distribution of all Gabor atoms used for MP decomposition of EG recorded during stabilization (reference ED) and other experimental period in frequency band 0-40 Hz (current ED).

4. Conclusions

The study shows significant shifts of majority energy frequency components during ischemia and their recovery after reperfusion. Further, MP confirmed subtle frequency changes within QRS complexes during the experiment. MP offers information about frequency components which are not so perceptible in the results from the wavelet transform which is used more frequently.

Acknowledgements

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