Symbolic transfer entropy-based premature signal analysis*

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In this paper, we use symbolic transfer entropy to study the coupling strength between premature signals. Numerical experiments show that three types of signal couplings are in the same direction. Among them, normal signal coupling is the strongest, followed by that of premature ventricular contractions, and that of atrial premature beats is the weakest. The T test shows that the entropies of the three signals are distinct. Symbolic transfer entropy requires less data, can distinguish the three types of signals and has very good computational efficiency.

Keywords: premature signal, symbolic transfer entropy, signal coupling

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1. Introduction

People have found the synchronization of coupled systems and related phenomena in many biological systems, such as cardiopulmonary interactions and the neural signal.[1,2] The detection of the presence of synchronization and the dominant direction of coupling between systems are very important. The direction and intensity are coupled by the mutual valuation of their ability to predict the magnitude of systematic observation, and can be extracted by using information theory methods.

In the description of information exchange between two related systems, mutual information is usually used. However, mutual information does not contain the dynamic and directional information. In order to study the dynamic and directional information shared between two systems, Schreiber[3] proposed transfer entropy in 2000.

Since the concept of transfer entropy was proposed, it has been widely used.[1,2] However, transfer entropy does have some deficits, such as the long length of the data required and sensitivity to noise, which restricts its application and generalization. Therefore, symbolic transfer entropy was proposed[4] to deal with the above mentioned disadvantages. Symbolic transfer entropy combines symbolic dynamics[5−11] and the transfer entropy method. By calculating the symbolic transfer entropy, the directional and strength information of the coupling system can be directly obtained, which is very convenient.

In this paper, we use symbolic transfer entropy to study the coupling strength between premature signals. The numerical calculation shows that it has very good computational efficiency in determining different coupling characteristics between the premature signals.

2. Theory

2.1. Symbolizing the time series

Assuming that the electrocardiogram (ECG) sequence is X, $X = \{x_0, x_1, x_2, \ldots, x_i, \ldots, x_N\}$, and the sequence length is N, sequence X is transformed into a sequence of symbols $S = \{s_1, s_2, \ldots, s_i, \ldots, s_N\}, s \in A$ $(A = 0, 1, 2, 3)$. The specific conversion method is as follows.

We calculate the mean values of the signals greater than zero and the signals less than zero of the sampled ECG signal separately, and they are denoted by u_1 and u_2, respectively. Then

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$$s_i(x_i) = \begin{cases} 0: & u_1 < x_i < (1+a)u_1 \quad \text{or} \quad (1+a)u_2 \le x_i < u_2, \\ 1: & (1+a)u_1 < x_i < \infty \quad \text{or} \quad -\infty < x_i < (1+a)u_2, \\ 2: & (1-a)u_1 < x_i < u_1 \quad \text{or} \quad u_2 \le x_i < (1-a)u_2, \\ 3: & (1-a)u_2 \le x_i \le (1-a)u_1, \end{cases} \tag{1}$$

where $i = 1, 2, \ldots, N$, and a is a constant parameter. If the value of a is too large or too small, the details in symbolizing the original time series into the symbolic sequences will be lost, and the dynamic information in the signals cannot be captured. Here we take $a = 0.05$.

2.2. Calculating the symbolic transfer entropy

Suppose $x_i = x(i)$, $y_i = y(i)$, $i = 1, \ldots, N$, which represent the two observed time series. The value of y_{i+1} is predicted by the previous samples x_i and y_i. And the deviation is quantified by the generalized Markov property, $p(x_{i+1}|x_i, y_i) = p(x_{i+1}|x_i)$, where p is the transition probability density. If no Markov deviation exists, which indicates that Y has no effect on X, then the transfer entropy can also be seen as the permutation entropy between $p(x_{i+1}|x_i, y_i)$ and $p(x_{i+1}|x_i)$.

The transfer entropy between sequences X and Y is defined as

$$T_{X\to Y} = \sum p(x_{n+1}, x_n^{(k)}, y_n^{(l)}) \log \frac{p(x_{n+1}|x_n^{(k)}, y_n^{(l)})}{p(x_{n+1}|x_n^{(k)})}, \tag{2}$$

where x_n and y_n represent the state at time n, and $x_n^{(k)}$ represents $x_n, \ldots, x_{n-k+1}$, usually k and l are taken to be 1.

Two sets of data of different leads are acquired simultaneously for the same individual, and they are symbolized and then denoted as S and J, respectively. Using formula (2), the symbolic transfer entropy can be calculated as

$$T_{S\to J} = \sum p(s_{n+1}, s_n^{(k)}, j_n^{(l)}) \log \frac{p(s_{n+1}|s_n^{(k)}, j_n^{(l)})}{p(s_{n+1}|s_n^{(k)})}. \tag{3}$$

3. Data analysis

Ten normal sinus rhythm signals (NOR) are taken from the MIT-BIH Normal Sinus Rhythm Database, and 10 atrial premature beats (APB) and 10 ventricular premature signals (PVC) are taken from the MIT-BIH Arrhythmia Database. Each piece of data contains two values from the left upper limb lead (aVL) and the unipolar chest lead (V6).

3.1. Symbolized signal sequences

To demonstrate the symbolized signal sequences, we symbolize a normal ECG signal with a length of 500, which is shown in Fig. 1.

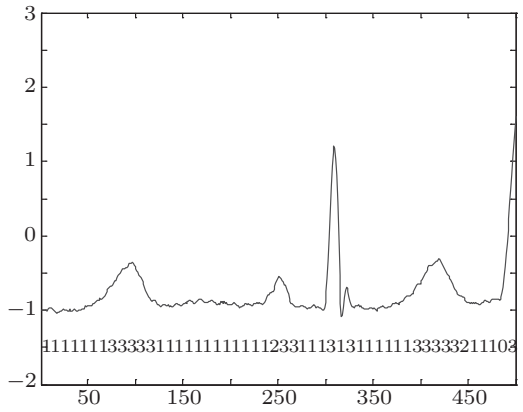


Fig. 1. The symbolized time series.

3.2. Symbolic transfer entropies of different length signals

For each of the three time series, the symbolic transfer entropy values between the aVL and V6 leads at different lengths are calculated. The 1000, 2000, 3000, ..., 8000 points are taken, respectively. The results are shown in Fig. 2.

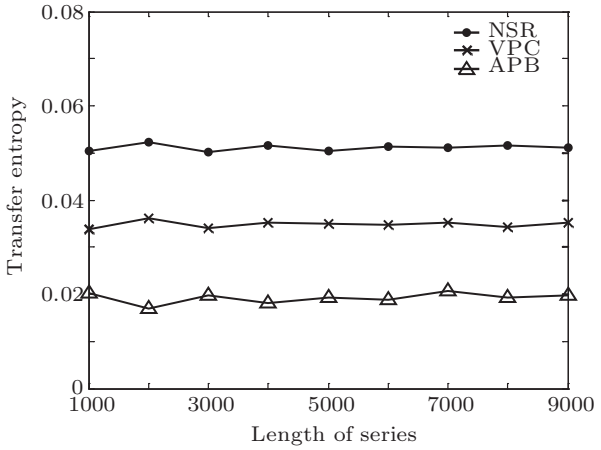


Fig. 2. The symbolic transfer entropies of different lengths.

The results show that the symbolic transfer entropies of the sequences are basically convergent after

reaching a certain length. So, the symbolic transfer entropy method requires less data and has a high computational efficiency.

3.3. Symbolic transfer entropies of three kinds of ECG signals

Ten samples are taken from normal signals, atrial premature beats and ventricular premature beat signals, and each sample has a length of 3000. The symbolic transfer entropies are calculated and shown in Fig. 3 and Table 1.

It can be found from Table 1 that the mean values of the symbolic transfer entropies for the three signals are 0.0528, 0.0351 and 0.0198, respectively, and all of them are greater than 0. This indicates that all of the coupling directions of the three signals change from the aVL lead to the V6 lead, and that the coupling strength of the normal signal is the strongest, that of the premature ventricular contractions is the second strongest, and that of the atrial premature beats is the weakest.

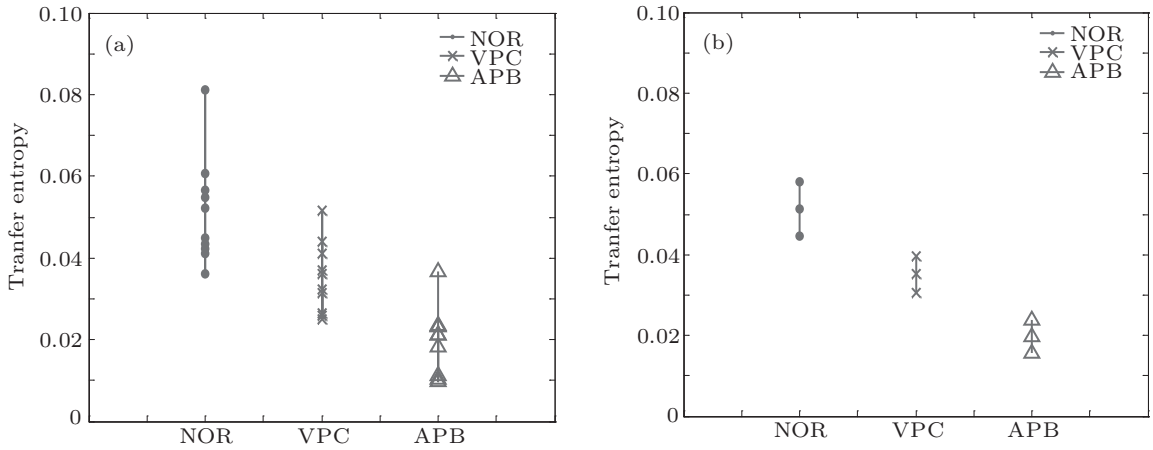


Fig. 3. (a) The symbolic transfer entropies of 10 samples of NOR, PVC and APB signals, and (b) their averages and standard deviations.

Table 1. The symbolic transfer entropies of three signals.

	1	2	3	4	5	6	7	8	9	10
NOR	0.0448	0.0434	0.0361	0.0412	0.0566	0.081	0.0607	0.0547	0.0521	0.0422
VPC	0.0362	0.0441	0.0412	0.0515	0.0249	0.0371	0.0313	0.0265	0.0323	0.0259
APB	0.0366	0.0211	0.0103	0.0231	0.0114	0.0097	0.0182	0.0212	0.0231	0.0236

Finally, the T test is performed. Comparing the premature ventricular contractions with the normal signals, the calculation shows $t = 3.845 > t_{0.05(18)}$, where t is the T test value. So at confidence level $P < 0.05$, the premature ventricular contractions and the normal signals have a significant difference. Therefore, the mean symbolic transfer entropy between the aVL and V6 leads of the premature ventricular signals is significantly less than that of the normal signals. Comparing the premature ventricular contractions with the atrial premature beats, the calculation shows $t = 2.917 > t_{0.05(18)}$. So at $P < 0.05$, the premature ventricular contractions and the atrial premature beats have a significant difference. A conclusion can thus be drawn that the mean symbolic transfer entropy between the aVL and V6 leads of the atrial premature beat is significantly less than that of the premature ventricular contraction.

4. Conclusion

In this paper, symbolic transfer entropy is used to analyze the coupling relationship between aVL and V6 leads for normal signals, atrial premature beats and ventricular premature beat signals. It is shown that all of the coupling directions for the three signals change from the aVL lead to the V6 lead. At the same time, it is found that the coupling strength of the normal signal is strongest, that of the premature ventricular contraction is the second strongest, and

that of the atrial premature beat is the weakest. The T tests show that the three signals are significantly different.

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