A NOVEL BLOCKING INDEX BASED ON SIMILARITY MEASUREMENT APPLIED IN DISTINGUISHING THE PATTERNS OF BLOOD PRESSURE SIGNALS AT DYNAMICALLY TRANSITIONAL SITUATION

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ABSTRACT

Acute mesenteric arterial occlusion is an abdominal catastrophe that carries high morbidity and mortality. The poor outcomes of this disease process are caused by the delay in initiating therapy because of the difficulties in making an accurate and timely diagnosis. In this study, we tried to conduct pattern analysis on blood pressure (BP) signal under simulated situation using an innovative measurement of similarity. The simulations of intestinal artery occlusion were conducted to two young healthy pigs to generate the recordings of blood pressure signals in dynamically transitional situation. Based on the distance measurement of similarity, non-clamping, non-relaxing, and blocking indexes are defined. Moreover, blocking index (BI) performs a good indicator for verifying the pattern of BP signal under the situation of clamping or relaxing. Finally, the analysis results show the feasibility of pattern analysis for identifying the underlying condition of circularity system.

Keywords: Arterial occlusion; Blood pressure; Similarity; Non-clamping index; Non-relaxing index; Blocking index.

INTRODUCTION

Mesenteric ischemia occurs as a result of compromised blood flow and oxygen delivery to the bowel. It results from an interruption in the blood supply to part or all of the small or large intestine. This disease can occur in both acute and chronic forms and can be further classified into arterial occlusive, venous occlusive, and nonocclusive mesenteric ischemia. The poor outcomes of this disease process are caused by the delay in initiating therapy because of difficulties in making an accurate and timely diagnosis. Traditionally, conventional angiography has been the standard for diagnosing mesenteric arterial ischemia. Currently, multidetector-row computed tomographic

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(MDCT) angiography is widely established noninvasive technique for assessing suspected mesenteric ischemia. However, due to the high cost MDCT angiography is not easily available in every hospital. Doctors rely on vital signs such as blood pressure, heart rate and concentration of oxygen in blood (SPO₂), to guess if it is due to the arterial occlusion from either embolus or thrombus. Hence, in this investigation, we tried to develop a new approach for diagnosing acute mesenteric arterial embolus and thrombus by measuring the pattern of blood pressure signal. Then, a pattern analysis method based on linguistic analysis algorithm is also developed in this investigation. And, an innovative indicator of blocking index using the measurement of similarity is defined for verifying the underlying situation of blood flow.

The measurement of the similarity between two complex signals was proposed by Yang et al. in 2003. They also applied the method of constructing phylogenetic trees to arrange different groups of samples on a branching tree to best fit the pair-wise distance measurements. Yang et al. also applied the measurement of similarity for an information categorization approach. The measurement of similarity is the output parameter of linguistic analysis algorithm and it is a kind of pattern analysis method. In this study, the measurement of similarity is applied for expressing the degree of similarity between the fluctuation patterns of two samples of BP signal.

Additionally, we extended the method of constructing phylogenetic trees for presenting the distances among time series of BP in situations of artery clamping and relaxing for different subjects. Thus, the non-clamping non-relaxing and blocking indexes are also defined using the measurements of similarity to verify the underlying situations of blood flow. Finally, the measurement of blocking index is applied to verify the pattern of time series of blood pressure signal in the situation of artery clamping or relaxing. Analysis result shows blocking index can sensitively identify bloodflow under clamping situation by a positive value and contrastive situation by a negative value.

**MATERIAL AND METHOD**

**The Experimental Surgical Operation**

In this investigation, we chose two male Lanyu-50 pigs for experiment. Their body weights are around 10-15 kg. After intramuscular injection of Zoletil (Zoletil 50 Vet; Virbac SA, Carros, France) 3-5 mg/kg, an intravenous line was established at the vein behind the ear. Oxymeter was applied on the tail. Other monitored biosignals included body temperature and ECG. Heating device includes heating blanket and air warming. Additional Zoletil was prepared for the requirement to achieve immobility before intubation. After intubation and confirming the positioning of endotracheal tube (size 5.0-5.5 mm internal diameter, with or without cuff), 4 mg pancuronium was injected intravenously. Subsequently, Zoletil 5 mg/kg and 4 mg pancuronium were given per hour. The recipient pig was anesthetized following the same procedures above, with additional central venous catheter (20G-22G-22G, BD) at the right internal jugular vein and an arterial catheter (20G) at the left femoral artery under cut-down procedure. Lactate Ringers solution, Hespaneder and whole blood (donated from other pigs) were administered to maintain adequate volume status (central venous pressure > 5 mmHg) and hemoglobin level (> 8 g/dl). Norepinephrine or epinephrine (bolus or continuous infusion) may be required to maintain systolic blood pressure > 100 mmHg, especially after graft reperfusion. At the end of surgery, if the hemodynamic profile was stable, we would try weaning from ventilator support.

**Data Recording**

In the experimentally surgical operation conducted to pig 1, pig's intestinal artery was blocked by clamping for a moment (e.g., one minute) and relaxed the clamping again for producing successive time series recording with two different situations and transition state between them. This procedure was repeated two times consecutively and four-minute time series recording of blood pressure signal as shown in Fig. 1. In the second experimentally surgical operation conducted to pig 2, several time series of blood pressure signal were recorded in different controlled situations. Those data were applied for certifying that we can measure the blocking index for sample of time series by comparing the referent patterns extracted from a different object.

**Method of Linguistic Analysis**

Based on the method of linguistic analysis proposed by Yang et al., we consider a blood pressure signal, \( \{x_0, x_1, x_2, \ldots, x_N\} \), where \( x_i \) is the voltage value of the \( i \)th sampling point of blood pressure recording. The signal can be simplified into binary sequences by mapping process, where the increase and decrease of voltage
values are denoted by 1 and 0. This mapping can be expressed as below:

\[ I_n = \begin{cases} 
0, & \text{if } x_n \leq x_{n-1}, \\
1, & \text{if } x_n \geq x_{n-1}.
\end{cases} \tag{1} \]

Digitalized patterns are convenient for us to characterize the pattern by a word. A segment of successive binary sequence of length 8 is symbolized by an 8-bit word. Each word represents a unique pattern of fluctuations in the time series. By shifting one sampling point at a time, a collection of 8-bit words over the whole time series is derived. This collection contains 256 different digital patterns and their occurrences frequencies. Thus, we obtain the ranks of frequency distribution. This set of ranks of words represents the statistical hierarchy of symbolic words of the original time series.

To define a measurement of similarity between two signals, a weighted distance, \( D_m \), between two symbolic sequences, \( S_1 \) and \( S_2 \), can be expressed as below:

\[
D_m(S_1, S_2) = \sum_{k=1}^{2^m} \left[ R_1(w_k) - R_2(w_k) \right] \cdot p_1(w_k) p_2(w_k) \cdot \frac{2^m - 1}{\sum_{k=1}^{2^m} p_1(w_k) p_2(w_k)} \tag{2}
\]

\( p_i(w_k) \) and \( R_i(w_k) \) represent occurrence frequency and rank of a specific word, \( w_k \), in time series \( S_i, i = 1 \) or 2.

Two time series with similar patterns of fluctuations have similar probabilities and ranks of words, and thus results in a smaller distance.

**Presenting the Correlation Among Samples by Constructing a Phylogentic Tree**

The method of constructing phylogenetic trees is a useful method to present the correlation among a group of samples. No matter what time, the series of blood pressure signal is affected by many different factors. But, the fundamental problem is how to go about verifying the effects caused by a different factor. Here, the phylogentic tree is a powerful tool to present the effects of different factors by tree structure. Moreover, the method of constructing phylogenetic tree is extended for establishing the target of designing a parameter of pattern analysis to identify the underlying situations of blood pressure signal.

**Blocking Index**

By consider the purpose of this study, we try to design a parameter for identifying the underlying situation (i.e., situation of artery clamping or relaxing) of blood flow. In this investigation, two extreme underlying situations
of artery clamping and relaxing are selected as two referent baselines. To show the characteristics of patterns for a sample of blood pressure signal within a narrow time interval and present the dynamic change of pattern, the rank order-frequencies of sample were compared with those two referent patterns. Thus, we define the weighted distance of linguistic analysis between rank order-frequencies of a sample and the referent pattern of artery clamping as non-clamping index. Similarly, the non-relaxing index is defined by the weighted distance between rank order-frequencies of sample and the referent pattern of artery relaxing.

Moreover, we manage to design a factor (e.g., blocking index) for identifying the underlying situation of blood flow. This factor should be positive when the pattern of blood pressure signal is similar to the referent pattern of clamping, but negative when the pattern of blood pressure signal is similar to the referent pattern of relaxing. So, the blocking index is defined by the following equation:

$$I_B = \frac{(I_{NR} - I_{NC})}{(I_{NR} + I_{NC})}$$  \hspace{1cm} (3)

Where $I_B$ means the blocking index; $I_{NR}$ is non-relaxing index; and $I_{NC}$ is non-clamping index.

However, the blocking index of $I_B$ is strongly affected by the referent patterns. In this investigation, three sets of referent patterns were applied for calculating the blocking index. Excluding the time series of transition state, we captured the time series in steady states of artery clamping and relaxing as the referent patterns of artery clamping and relaxing. Also, the referent time series of artery clamping and relaxing were captured from two pigs. Thus, referent time series were mapped to binary sequences and characterized the digital patterns by rank order-frequency of word. The characteristics of the first and second sets of referent patterns are expressed and stored as the format of rank order-frequency. Finally, the third set of referent patterns was derived by mixing the first two sets of referent patterns. The method of mixing is conducted by averaging the occurrence frequencies of words for the referent patterns extracted from different objects in the same situation. The new rank order-frequencies present the characteristics of mixed referent patterns.

RESULTS

For the purpose of proving that linguistic analysis can be applied to distinguish the characteristic patterns of time series in different situations, we extracted eight samples of blood pressure signal from the recording of the first surgical operation. The eight samples can be assorted to two groups (i.e., experimental and control groups). The samples of experimental group were extracted as a twelve-second time series in the steady state of artery clamping. Similarly, samples of control group were extracted as a twelve-second time series in the steady state of artery relaxing. The time intervals of eight samples are shown in Table 1. Then, the weighted distance of linguistic analysis between arbitrary two samples was derived and shown in Table 2.

Table 1. Notations and Time Intervals of Sampling Time Series of Experimental and Control Groups. The Columns with Grey Background Mean Experimental Samples and the Columns with White Background Mean Control Samples.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Interval</td>
<td>0:18</td>
<td>0:30</td>
<td>1:10</td>
<td>1:30</td>
<td>2:28</td>
<td>2:40</td>
<td>3:18</td>
<td>3:30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0:30</td>
<td>0:42</td>
<td>1:22</td>
<td>1:42</td>
<td>2:40</td>
<td>2:52</td>
<td>4:00</td>
<td>3:42</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. The Results of Comparisons Among the Samples of Experimental and Control Groups. In this Table, Columns with Lightly Grey Background Mean that Two Samples for Comparison are Both Experimental or Control Samples and Columns with Dark Gray Background Mean the Sample Belong to Experimental Group.

<table>
<thead>
<tr>
<th>Weighted Distance</th>
<th>ID of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 3. The Averages and Standard Deviations of Weighted Distances for Three Types of Combinations by Samples from Experimental and Control Groups. These Types of Combinations can be Sorted as Two Experimental Samples, Two Control Samples, and an Experimental Sample Plus a Control Sample.

<table>
<thead>
<tr>
<th>Types of Two Samples for Comparing</th>
<th>Average Distance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two experimental samples</td>
<td>0.004030</td>
<td>0.002096</td>
</tr>
<tr>
<td>Two control samples</td>
<td>0.004993</td>
<td>0.001433</td>
</tr>
<tr>
<td>Experimental and control samples</td>
<td>0.029767</td>
<td>0.002311</td>
</tr>
</tbody>
</table>

According to the results shown in Table 2, the weighted distances between experimental and control samples are significantly bigger than those between samples of same group. Averages and standard deviations of weighted distances for intra-group samples of experimental group, intra-group samples of control group, and inter-group samples are shown in Table 3. In Fig. 2, there are significant differences between the results of weighted distances for inter-group and intra-group. Thus, algorithm of linguistic analysis works for distinguishing two different patterns of time series.

Furthermore, we conduct the pattern analysis on the four-minute time series of blood pressure signal. For the purpose of deriving a continuous analysis result, we capture four-second time series, the time series between $t-2$ and $t+2$, as the sample to represent the pattern of blood pressure signal at time point $t$. And, every sample of time series is compared to the referent patterns of artery clamping and relaxing to derive the analysis results of non-clamping and non-relaxing indexes. The changes of non-clamping and non-relaxing indexes for the overall recording of the first surgical operation are shown in Fig. 3. In this figure, a complementary relationship exists between non-clamping and non-relaxing indexes. When one of non-clamping and non-relaxing indexes is increasing the other one is decreasing.

However, by considering the essential differences between patterns of two different objects, a similar surgical operation was conducted to the second pig. The second set of referent patterns of artery clamping and relaxing are also extracted for comparing with the referent patterns extracted from the second surgical operation. The weighted distances among four referent patterns are shown in Table 4. Moreover, the comparisons among results of linguistic analysis for four referent patterns are shown in Fig. 4 by constructing a

![Fig. 2](image1.png)  
**Fig. 2** The averages and standard deviations of weighted distance for three different combinations of experimental and control samples.

![Fig. 3](image2.png)  
(A) The recording of original blood pressure signal. (B) Time series of non-clamping and non-relaxing indexes. Grey line represents the non-relaxing index and black line represents the non-clamping index.
Table 4. The Weighted Distances Between Four Referent Patterns (i.e., Referent Patterns Extracted from Two Different Pigs in Two Different Situations).

<table>
<thead>
<tr>
<th>Pig</th>
<th>Clamping</th>
<th>Relaxing</th>
<th>Clamping</th>
<th>Relaxing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig 1 Clamping</td>
<td>0</td>
<td>0.0268</td>
<td>0.0052</td>
<td>0.0265</td>
</tr>
<tr>
<td>Relaxing</td>
<td>0.0268</td>
<td>0</td>
<td>0.0256</td>
<td>0.0060</td>
</tr>
<tr>
<td>Pig 2 Clamping</td>
<td>0.0052</td>
<td>0.0256</td>
<td>0</td>
<td>0.0250</td>
</tr>
<tr>
<td>Relaxing</td>
<td>0.0255</td>
<td>0.0060</td>
<td>0.0250</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 4 A rooted phylogenetic tree generated according to the weighted distance between referent samples for two different pigs in two different situations.

phylogenetic tree. And, in this graphical expression, we find the part of weighted distance caused by individuals of subjects is smaller than the rest part of weighted distance caused by underlying situations.

Additionally, the relationship between non-relaxing and non-clamping indexes can be visualized by straightening the phylogenetic tree to a one-dimension diagram shown in Fig. 5. Moreover, we obtain the third set of rank order-frequencies of referent patterns by averaging the occurrence frequencies of 256 8-bits words. In this figure, end points show two extreme conditions (i.e., artery clamping and relaxing) of three sets of referent patterns. When the pattern of blood flow is different from patterns of these two extreme conditions, the characteristic of pattern of blood pressure signal in this situation may be represented by appropriate point, marked by cross, between two end points. Horizontal distance between the point with cross and the left end-point represents non-relaxing index. Similarly, horizontal distance between the point and the right end-point represents non-clamping index. Thus, the relationship of complement between non-relaxing and non-clamping indexes is clearly expressed.

Furthermore, three sets of referent patterns of artery clamping and relaxing were applied for pattern analysis by blocking index. In Fig. 5, three sets of non-clamping and non-relaxing indexes can be represented by the horizontal distances between the point with cross and three sets of end-points. Thus, three different blocking indexes are obtained by applying different set of referent patterns.

In Fig. 6, analysis results of three blocking indexes for the recording of the first surgical operation are shown with different colors. The line of dark grey presents the time series of blocking index obtained by comparing to the first set of referent patterns. The line of light grey presents the blocking index obtained by comparing to the second set of referent patterns. The line of black presents results of the third set of referent patterns. In this figure, the recording of blood pressure signal for the first surgical operation had been analyzed by comparing with three sets of referent patterns and the results are noted by the first blocking index (B11), the second blocking index (B12), and the third blocking index (B13). Because of the fact that the first set of referent patterns had also been extracted from recording of the first surgical operation, the correlation between

Fig. 5 Schematic of non-relaxing and non-clamping index shows the relationship between these indexes. In this figure, cross mark represents as assumed patterns between the referent patterns of artery clamping and relaxing. Three pairs of non-clamping and non-relaxing indexes are illustrated by the horizontal distance between the cross mark and different end-points.
Fig. 6  (A) The original signal of blood pressure recorded in the first surgical operation. (B) Blocking indexes by comparing with referent patterns extracted from different objects. The black line presents blocking index for comparing with the mixed referent patterns (e.g., BI3). The lightest gray line presents that for comparing with the referent patterns extracted from pig 2 (e.g., BI2). Then, the dark gray line presents that for comparing with the referent patterns extracted from pig 1 (e.g., BI1).

recording and the first set of referent patterns is strong. Comparing the results of three blocking indexes, the absolute value of the first blocking index is the biggest one of them. According to the essential purpose of designing the blocking index, we manage to design this parameter being a positive value for a underlying situation of artery clamping and being a negative value for a underlying situation of artery relaxing. Under idealized condition, blocking index should be +1 for the underlying situation of artery clamping and -1 for the underlying situation of artery relaxing. Here, we find BI1 results the performance similar to the idealized conditions. Therefore, we conclude that BI1 performs as the most sensitive indicator.

**DISCUSSION**

In this paper, three different baselines (e.g., referent patterns) were applied for pattern analysis. Because of the limited number of surgical operation conducted in this investigation, those baselines are the only options for us. They are definitely not the optimal solutions for pattern analysis. Thus, how to define an optimal baseline for pattern analysis is still the main problem. However, based on the results of pattern analysis, the baseline extracted from the same object in which the analyzed time series was extracted will get good performance for pattern analysis. Contrastively, the selected baseline and analyzed time series extracted from the two different objects will reduce the performance for pattern analysis. The mixed referent patterns can be applied for a common baseline for two objects in this investigation. Thus, a set of mixed referent patterns generated by averaging the referent patterns extracted from sufficient number of objects may be a general baseline for pattern analysis.

Based on the results of this investigation, we should consider the possibility of developing an online blood pressure pattern monitoring system. In the practical procedure of signal processing, digitalized time series of blood pressure signal can be mapped to binary sequence and applied for calculating rank order-frequency easily. Moreover, the algorithm of pattern analysis by blocking the index is sample and powerful. So, when a general baseline or the criterion for setting baseline can be built up, to implement a practical application for online blood pressure pattern analysis is not a difficult target. On the other hand, blood embolisms in different positions will cause different effects upon the blood pressure pattern. Concerning those effects, more simulations and investigations for blood embolisms in different positions should be conducted in future research. Maybe a multi-scale blocking index can be developed for verifying different situations of blood embolisms.

Finally, some anesthetics were injected to pigs' bodies during the experimentally surgical operations. Different anesthetics will cause different side effects for physiological conditions. Those side effects were
not considered for pattern analysis. Furthermore, the amplitude of blood pressure rose significantly when the intestinal artery was clamped. During the first surgical operations, the situation of artery clamping or relaxing can be verified by observing change of amplitude of blood pressure signal. We are also interested in what will happen if some blood pressure control agents are applied for controlling the amplitude of blood pressure on the same level before and after artery clamping. Does the pattern analysis still work for verifying the patterns of blood pressure signal in situations where there is artery clamping and relaxing?

CONCLUSIONS

In this study, a novel blocking index was applied for pattern analysis successfully. According to the results of pattern analysis, the blocking index of a sample in the situation of artery clamping has positive value and that in the situation of artery relaxing has negative value. However, the results of blocking index will depend on the baseline we define. How to define a general baseline suitable for most of objects is a crucial issue for pattern analysis. On the other hand, how to apply blocking index as a real-time parameter for monitoring pattern of blood pressure and the effects of drugs applied for blood pressure control will be discussed in the future.

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