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Analysis and Evaluation of Vascular Sounds in Hemodialysis*

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***Abstract*— A vascular access is required for hemodialysis. Because the vascular access is an important lifeline for patients with renal failure, its monitoring and management are essential. The vascular access is typically monitored through auscultation of vascular sounds because these sounds provide some indication of access patency; however, this is not a quantitative assessment. The objective of this study is to develop a quantitative assessment of vascular sounds in hemodialysis. We propose several parameters to evaluate discontinuities in sound power and to specify the shape of the power spectrum, using signal processing techniques such as the theory of spectral distance with autoregressive model and the nonlinear closing operation from the field of mathematical morphology, which is essential for robust segmentation of waveform. In our demonstrations, abnormal vascular sounds are seen to exhibit different parameters compared to normal sounds. This shows that these parameters may be useful for assessing conditions of vascular sounds.**

Keywords: Vascular sounds, Autoregressive model, Hemodialysis, Quantitative assessment

I. INTRODUCTION

Vascular access is required for renal therapy with hemodialysis treatments. A vascular access for hemodialysis is constructed under the skin of the arm of a patient and is fashioned by the direct anastomosis of an artery to a vein. Because the vascular access is an important lifeline for patients with renal failure, its monitoring and management are an indispensable part of daily care. Auscultation of vascular sounds, which is the simplest monitoring method, is non-invasive and can be used not only by medical staff but also by patients themselves. Although vascular sounds differ from person to person and may vary with the passage of time, changes in vascular sounds can predict vascular-access trouble. In current medical practice, medical staff listen to vascular sounds with a stethoscope as part of routine care and usually classify the sounds as follows:

1) normal sounds, typically continuous and low-pitched
2) high-frequency stenotic sounds that have a high-frequency component and often include sharp spectrum components
3) discontinuous stenotic sounds such as components that are synchronous with the cardiac cycle.

It is valuable to track and classify vascular sounds because the characteristics of vascular sounds can be an informative indicator of vascular access conditions. A quantitative assessment and classification of vascular sound could preventively diagnose access trouble at an early stage. In recent years, several studies have attempted to detect the acoustic characteristics generated by occluded blood vessels[1]-[6], but these techniques may be insufficient to detect the characteristics of vascular sound changes caused by vascular stenosis. The objective of our study is to develop a novel method for the quantitative assessment and characterization of vascular sounds. We utilize signal processing techniques including autoregressive model and Itakura spectral distance[7][8] to characterize high-frequency stenotic sounds. Mathematical morphology[9][10] plays an important role in waveform segmentation in our method. We derive five parameters that represent the degree of discontinuity of the various vascular sounds and thus allow quantitative assessment and characterization of the sounds. We demonstrate the effectiveness of our proposed method and parameters.

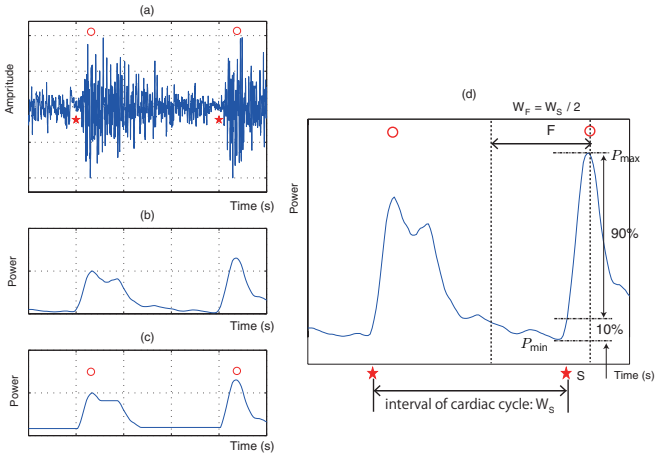

Fig. 1. The automatic segmentation process. (a) Original vascular sound waveform. (b) Envelope of the original signal. (c) Morphological closing of the envelope by the flat structure element. (d) Summary of the determination of border points using peak positions and signal power.

II. METHODS

The evaluating algorithm consists of time and frequency domain analysis with waveform segmentation. The first stage of time domain analysis segments a vascular sound waveform to correspond to each heartbeat. The second stage of time domain analysis provide five parameters that are used for the evaluation of the discontinuities of vascular sounds. Subsequent frequency domain analysis identifies high-frequency stenotic sounds using the Itakura spectral distance and poles in autoregressive models.

A. Segmentation of vascular sounds

The vascular sounds vary in systole and diastole. The segmentation of vascular sounds is important to obtain the acoustic characteristics of vascular sounds in each cardiac

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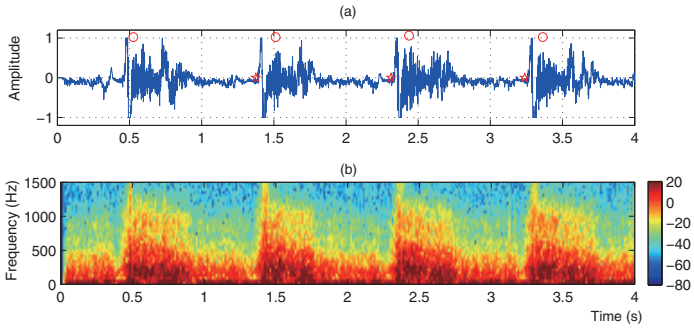

Fig. 2. Discontinuous vascular sound. (a) Wave form (b) Spectrogram

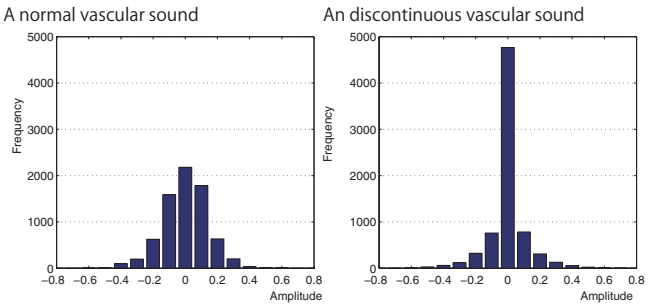

Fig. 3. Histogram of vascular sound amplitude for one cardiac cycle, showing the difference in kurtosis for normal and abnormal vascular sounds.

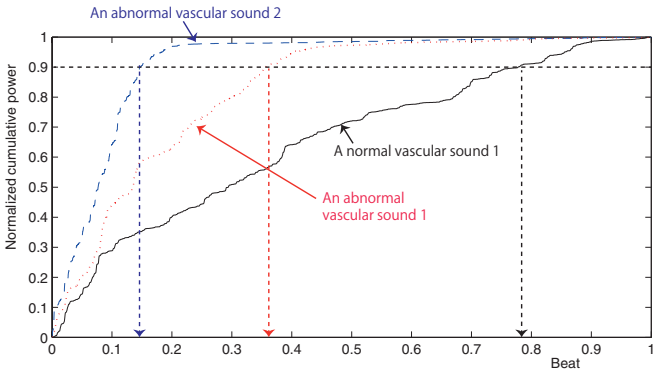

Fig. 4. Normalized cumulative power traces in normal and abnormal vascular sound in a cardiac cycle. The solid line, dotted line, and broken line indicate normal sound, abnormal sound (Case1) and abnormal sound (Case2), respectively.

interval. We automatically segment a sampled vascular sound to correspond to heartbeats as follows.

1) Peak detection: We eliminate unwanted frequency components using a bandpass filter with cutoff frequencies of 100 Hz and 900 Hz. The envelope is calculated using a triangular moving average of the square of the filtered signal. This envelope, however, often still contains multiple local maxima, and is not suitable for determining the peak of each segment. For this reason, we employ the nonlinear closing filter of mathematical morphology to specify a single peak position of the envelope within each segment. In the closing process, we use a flat structure function whose width is determined using the auto-correlation of the envelope.
2) Setting borders: We define the border as the point closest to the peak among the points where power is less than $(P_{\max} - P_{\min}) \times 0.1$ in the latter half of the interval shown in Fig. 1 , where $P_{\max}$ and $P_{\min}$ are the maximum and minimum values of the square of the filtered signal in the area, respectively. One cardiac interval of the sound is shown in Fig. 1 . The star sign on the figure designates the determined starting point of a heartbeat.

B. Time domain analysis

The vascular sound will often become intermittent as stenosis progresses. Fig. 2 shows a discontinuous vascular sound. We use five parameters to evaluate the discontinuity of sound power in each cardiac cycle:

(a),(c) and (d) are derived from the signal, which is the square of signal filtered using a high-pass filter with a cutoff frequency of 100 Hz and 100th-order zero-phase FIR filter. These filter parameters are given heuristically, and the filter is designed using MATLAB fir1 function.

(a) Energy ratio: We define waveform energy ratio(WER) as the energy ratio in vascular sounds. WER is obtained as $E_{\mathrm{P}}/E_{\mathrm{A}}$, where E_{P} and E_{A} are the total amount of energy in the former and latter half of W_{S} in each cardiac cycle, respectively. W_{S} is shown in Fig. 1 (d).

(b) Kurtosis in waveform signal: We pass the signal through a 100th-order zero-phase FIR high-pass filter with a cutoff frequency of 100 Hz and calculate the kurtosis of the power in each cardiac cycle. Fig. 3 shows the histogram of the waveform amplitude for normal and abnormal vascular sounds.

(c) Number of low-energy segments : The resulting energies are divided into ten equal parts by each cardiac cycle. Then, the energy on each segment is calculated. Finally, we count the number of segments that have less than 20% of the maximum energy value . We define that number as N_{low}.

(d) $R_{90\%}$ for integrated power: We denote the total waveform power in each cardiac cycle as E_{total}. Then, we define $R_{90\%}$ as the interval to reach 90 % of E_{total}. Fig. 4 shows the traces of cumulative waveform power in normal and abnormal vascular sounds.

(e) Rate of decrease: We obtain the filtered signal using a 100th-order zero-phase FIR high-pass filter with a cutoff frequency of 100 Hz. The power waveform, which is represented using a triangular moving average of the square of the filtered signal, is fitted to $A\exp(-t/\tau)$.

C. Frequency domain analysis

We quantify the shape of spectrum using an autoregressive model with the Itakura distance measurement and fractional bandwidth w_i in each segment. The autoregressive model is

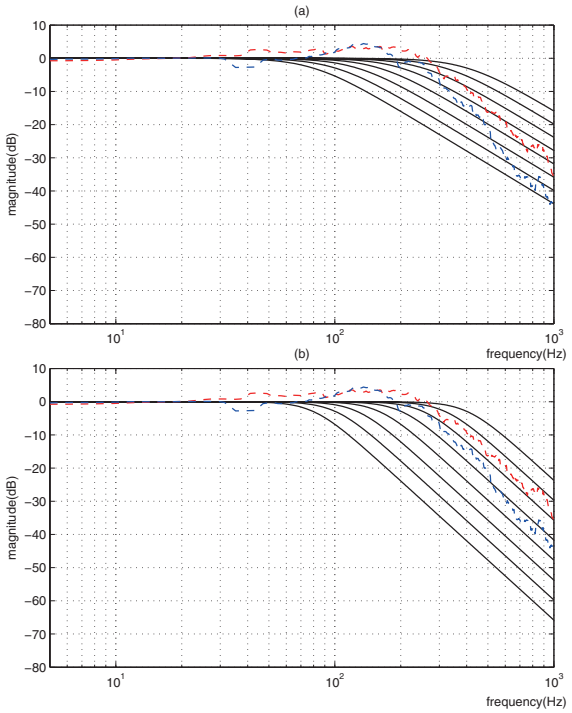

Fig. 5. Reference patterns. (a) Second order patterns. (b) Third order patterns.

obtained from the signal after the application of a high-pass filter with a cutoff frequency of 20 Hz and order 20. The sampling frequency is 2 kHz, the autoregressive order is 20, and 512 points are used as input to the autoregressive model.

- Measurement of Itakura distance: The following equations give 20 reference patterns[11].
  (a) Second-order patterns.

$$P(f) = 1/(1+(f/f_{c,n})^4)$$
$$(f_{c,n} = 100 \times 2^{n/5} \quad n = 0-9)$$

  (b) Third-order patterns.

$$P(f) = 1/(1+(f/f_{c,n})^6)$$
$$(f_{c,n} = 100 \times 2^{n/5} \quad n = 0-9)$$

  Fig. 5 shows the reference patterns for the measurement of the Itakura distance. We calculate the Itakura distance between these reference patterns and the value derived from the intended sound using the autoregressive coefficient.
- Measurement of fractional bandwidth: We suggest a specification method using the poles of the autoregressive model[12]. The transfer function of the autoregressive model is $H(z) = 1/A(z)$, and the poles are the solutions of $A(z) = 0$, denoted by $z_i \;\; i = 1, \cdots, p$. The pole frequencies and bandwidths are given by $f_i = \theta_i/2\pi T$ and $b_i = -\log r_i/\pi T$, respectively, where T is the sampling period[13]. We define w_i as the fractional bandwidth b_i/f_i. The spectral peak in $|H(e^{j\omega T})|$ having the highest amplitude is defined as P_1, the one having the second highest power is P_2, and P_3, P_4, P_5 are defined in the same manner. P_1 to P_5 are detected from frequencies of less than 900 Hz, which may include the main frequency range of vascular sounds. P_1 to P_5 are used in the processing of poles.

TABLE I
CALCULATED PARAMETERS FOR NORMAL AND ABNORMAL SOUNDS

	WER	Kurtosis	N_{low}	$R_{90\%}(\%)$	τ
N1	0.459	1.489	2.375	77.898	0.237
N2	0.344	1.291	2.167	75.537	0.248
A1	0.083	8.240	7.000	19.463	0.096
A2	0.048	7.555	7.000	38.048	0.059
A3	0.045	6.152	5.800	33.873	0.143
A4	0.152	4.686	5.900	53.598	0.080

III. RESULTS AND DISCUSSION

The results of vascular sound analysis in time domain are presented in Table 1. N1 and N2 are normal vascular sounds, and A1 to A4 indicate various abnormal vascular sounds including a discontinuous vascular sound. WER, $R_{90\%}$, and τ are at least 50% lower for abnormal sounds than for normal sounds, and Kurtosis and N_{low} are more than 50% higher for abnormal sounds than for normal sounds. Thus, our proposed parameters can distinguish discontinuous vascular sounds from normal sounds. The frequency domain analysis is shown in Fig. 6 and Fig. 7. Fig. 6 (c) and Fig. 7 (c) show the result of the Itakura spectrum distance. The Itakura spectrum distance of high-frequency sounds from a reference pattern is large because high-frequency vascular sounds feature a sharp spectrum. A normal sound is smaller in terms of the Itakura spectrum distance than an abnormal sound, and typically has a distance of close to 0. Fig. 6 (d) and Fig. 7 (d) show the pole frequencies with the fractional bandwidth being less than 0.1. Since the fractional bandwidths in the normal sound are almost greater than 0.1, only a few dots are shown in Fig. 6 (d). On the other hand, since the fractional bandwidths of the sharp spectral peaks of the high-frequency vascular sounds are mostly less than 0.1, the dots corresponding to these sharp spectral peaks are clearly shown in Fig. 7(d). We conclude that we can characterize normal and abnormal vascular sounds using the proposed methods.

IV. CONCLUSIONS

In this study, we proposed several parameters for the evaluation of discontinuities in vascular sound power and the spectral classification of continuous vascular sounds within a one-heartbeat period in order to extract signs of abnormality. The proposed method uses processing techniques such as autoregressive modeling and the nonlinear closing operation in mathematical morphology. The morphological transformation is an indispensable part of our method for the robust segmentation of waveform. For abnormal vascular sounds, the proposed parameters differ significantly from the normal case. It is concluded that we can evaluate several important features of normal sounds and abnormal sounds by using

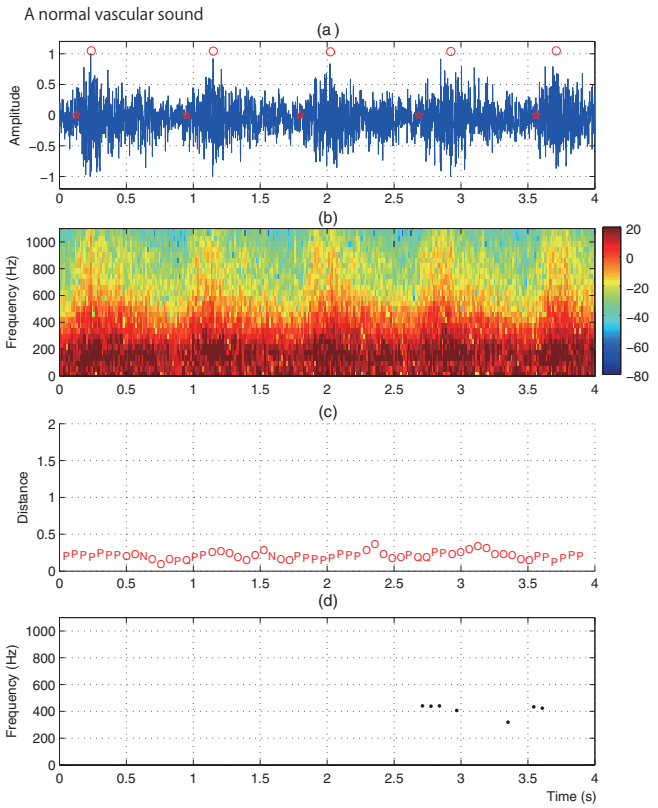

Fig. 6. Analysis of spectrum for a normal vascular sound. (a) Waveform. (b) Spectrogram. (c) Spectral distance. (d) Pole frequencies. N sign: 3rd-order $f_{c,3}$, O sign: 3rd-order $f_{c,4}$, P sign: 3rd-order $f_{c,5}$, and Q sign: 3rd-order $f_{c,6}$ in (c).

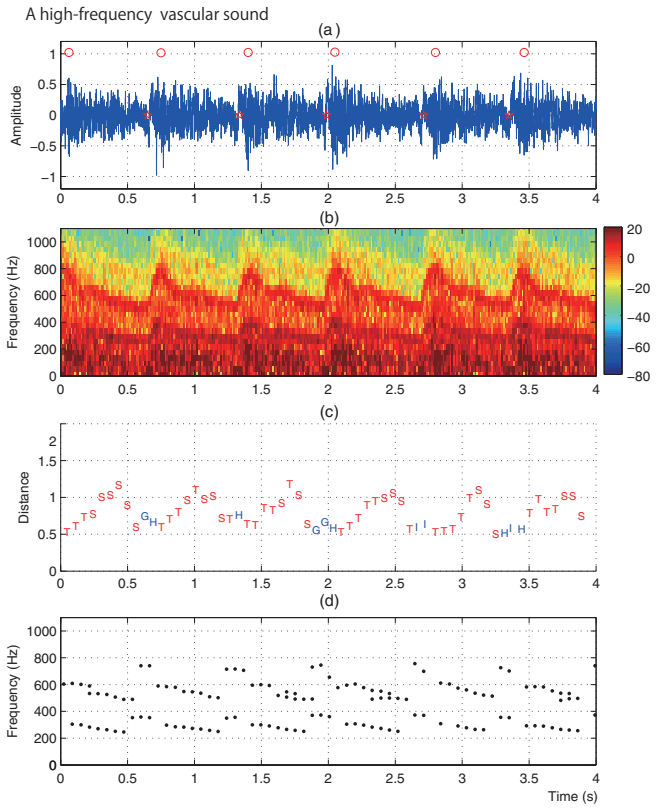

Fig. 7. Analysis of spectrum for a high-frequency vascular sound. (a) Waveform. (b) Spectrogram. (c) Spectral distance. (d) Pole frequencies. F sign: 2nd-order $f_{c,5}$, G sign: 2nd-order $f_{c,6}$, H sign: 2nd-order $f_{c,7}$, I sign: 2nd-order $f_{c,8}$, R sign: 3rd-order $f_{c,7}$, S sign: 3rd-order $f_{c,8}$, and T sign: 3rd-order $f_{c,9}$ in (c).

the proposed parameters. In the future, we are planning to validate the clinical applicability of these parameters, and further studies using various patient's vascular sounds are needed to evaluate performance of the algorithm.

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