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**Articles**

# Evaluation of vascular access function by shunt murmur analysis of hemodialysis patients using a simulated vascular stenosis model

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## I. Introduction

Shunt murmur auscultation is conducted in many dialysis facilities on an everyday basis because it can easily be performed by any staff member in any setting and is highly portable with no requirement for an electrical drive source. When a vascular access (VA) is functioning properly, a low-pitched shunt murmur with a continuous low-frequency component (below approximately 300 Hz) as the main component is audible on auscultation. When VA function is poor, a high-pitched shunt murmur with an intermittent high-frequency component (approximately 500–800 Hz) as the main component is audible instead. However, no standardized criteria have been devised for the evaluation of VA function using shunt murmurs, and the assessment criteria vary according to staff experience and individual judgment. Dialysis staff must be trained and experienced if they are to perform a proper evaluation of reduced VA function from stenotic murmurs.

We have previously devised a new VA functional assessment technique that is noninvasive, quantitative, and objective, by conducting time-frequency analysis via the wavelet transformation of shunt murmur signals measured with an accelerometer. The magnitude of the amplitude spectrum of each frequency component is then displayed by color map imaging. We obtained baseline time-frequency analysis image data for shunt murmurs measured in dialysis patients with properly functioning VAs and time-frequency analysis image data for shunt murmurs subsequently measured over time for comparison, then calculated the normalized cross-correlation coefficient R, which expresses the concordance between these images. Our results demonstrated the feasibility of quantitative monitoring of functional declines in VA from changes in the frequency domains of shunt murmurs over time. However, although the association between stenosis rates and the acoustic characteristics of shunt murmurs is explained qualitatively in terms of the association between shunt murmur frequency and vascular inner diameter, with a low pitch associated with a large inner diameter and a high pitch with a small in-

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ner diameter, no quantitative investigations of this association appear to have been reported. In this study, we created an arteriovenous fistula (AVF) model consisting of a TOUGHSiLON gel tube simulating vascular elasticity and a Y-shaped tube connector simulating the arteriovenous anastomosis, with the objective of carrying out a quantitative evaluation of changes in the acoustic characteristics of shunt murmurs resulting from increases in the stenosis rate, number of stenoses, and stenosis length. We investigated the effects of differences in stenosis conformation on the acoustic characteristics of shunt murmurs by calculating R values from simulated shunt murmurs measured in AVF models with different numbers and lengths of stenosis.

## II. Experimental Methods

### 2-1. Simulated shunt murmur measurement and calculation of R in AVF models

As an AVF model to simulate a properly functioning VA, we cut off the end of a polypropylene Y-shaped tube connector (inner diameter, 6 mm; external diameter, 8 mm; bifurcation angle, 60°) on the outflow vein side at a distance of 10 mm from the bifurcation. To reproduce a simulated shunt murmur to provide the criterion for a properly functioning VA, we connected a TOUGHSiLON gel tube (inner diameter, 6 mm; outer diameter, 8 mm; length, 150 mm; tensile strength, 3.1 MPa, TANAC Co., Ltd) to the outflow vein side of the Y-shaped tube connector. Silicone rubber tubes (inner diameter, 6 mm; outer diameter, 8 mm; LABORAN silicone tube) were connected to the inflow artery and peripheral artery sides of the Y-shaped tube connector, simulating the side-to-end (artery-to-vein) anastomosis that comprises the standard AVF.

To investigate changes in simulated shunt murmurs caused by different lengths and rates of stenosis, we then produced stenotic parts by taking acrylic cylinders measuring 6 mm in diameter and either 10 mm or 20 mm in length and boring holes in their center ranging in diameter from 4.8 mm (20% stenosis) to 1.2 mm (80% stenosis), in 20% increments. These stenosed parts were inserted in the outflow vein side of the Y-shaped tube connector and fixed in place with adhesive, after which a TOUGHSiLON gel tube was connected to create AVF models simulating eight different types of stenotic lesion in the outflow vein downstream from the anastomosis. By connecting a TOUGHSiLON gel tube to these, four types of AVF model simulating stenotic lesions in the outflow vein downstream from the anastomosis site were also prepared. To measure simulated shunt murmurs generated in the outflow veins of these AVF models, we placed the TOUGHSiLON gel outflow vein in a biological phantom with acoustic impedance simulating that of the human body (food-quality konjac, speed of sound [C], 1491 m/s; density [ρ], 1.23 g/cm$^3$; acoustic impedance [$Z = \rho \times C$], $1.83 \times 10^6$ Pa･s/m) so that the distance between the phantom surface and upper part of the outflow vein was ≤ 0.6 cm. The outlet of a multifunctional arteriovenous pump (maximum pump ejection volume, 2000 ml/min; maximum pump ejection pressure, 750 mmHg) was connected to the inflow artery of the AVF model by a 1.8-m-long silicone rubber tube (inner diameter, 6 mm; outer diameter, 8 mm). This was set to a pulse rate of 60 beats/min, and a duty ratio expressing the proportions of systolic and diastolic phases of the heart of 35% (systolic:diastolic ≒ 1:2). To simulate the blood pressure in hemodialysis patients, high and low pulsatile flow outputs were adjusted so that maximum pressure within the tube upstream of the Y-shaped tube connecter was 120 mmHg and minimum pressure was 80 mmHg. Maximum and minimum pressures were constantly monitored with a bedside monitor during the experiments. Circulating flow ($Q_0$, ml/min) within the AVF at each stenosis rate was calculated using a measuring cylinder.

An Electret condenser microphone (ECM-PC60, Sony Marketing Inc) was attached to the surface of the biological phantom at a distance of 20 mm from the Y-shaped tube connector tip. The simulated shunt murmur at this location was measured with a digital voice recorder at 10-s intervals. Simulated shunt murmur signals obtained from each model were analyzed using Wavelet-Disp and WaveletBitmapAnalyzer dedicated bioacoustics analysis software. In this analysis, we attempted to quantify changes in simulated shunt murmurs associated with a graduated increase in the stenosis rate, by obtaining baseline data for simulated shunt murmur signals measured in an AVF model with no stenosis (0% stenosis) and comparison data for simulated shunt murmur signals in each model. We then calculated the normalized cross-correlation coefficient R, which expresses the concordance between images that are time-frequency analyses results obtained by wavelet transformation of the baseline and comparison data (complete concordance = 10,000; complete mismatch = 0; $0 \leq R \leq 10{,}000$).

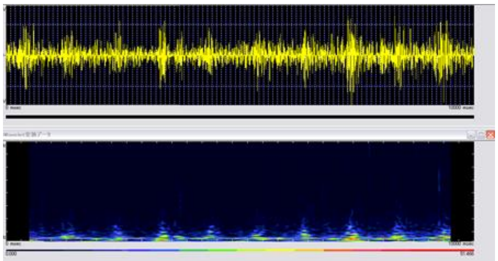
### 2-2. Simulated shunt murmur measurement and calculation of R in AVF models with multiple stenotic lesions

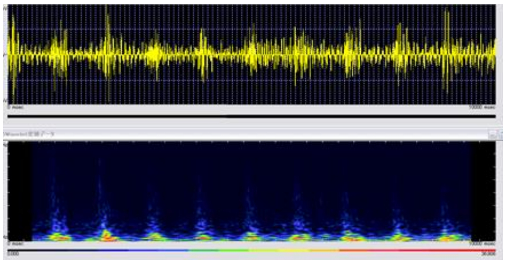
To AFV models with 10-mm-long stenotic parts inserted, we attached a TOUGHSiLON gel tube into which another stenotic part with an internal diameter that varied from 4.8 mm to 1.2 mm in 20% increments had been inserted. The insertion site was 10 mm from the tip of the Y-shaped tube connector, and the stenosed part was secured with a cable tie to prevent dislodgment from the TOUGHSiLON gel tube. We produced four different AVF models with multiple stenotic lesions in the outflow vein downstream of the anastomosis (upstream stenosis rate–downstream stenosis rate: 20%–20%, 40%–40%, 60%–60%, and 80%–80%). Simulated shunt murmurs were measured at two different measurement sites: 1) 5 mm from the Y-shaped tube connector tip, midway between the two stenoses; and 2) 5 mm downstream from the stenosed part placed in the TOUGHSiLON gel tube, following the experimental method described in Section 2-1.

## III. Experimental Results

### 3-1. R values calculated from simulated shunt murmurs in AVF models

We measured simulated shunt murmurs in the AVF models with downstream stenoses and calculated the R values. ***Figure 1*** shows simulated shunt


**(a)** stenosis rate: 0 %


**(b)** stenosis rate: 20 %

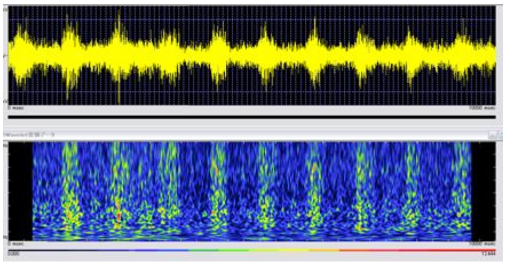

**(c)** stenosis rate: 80 %

***Fig.1*** Simulated shunt murmur signals and results of wavelet transformations (10-mm-long) murmur signals measured in the model with no stenosis and models with simulated 10-mm-long 20% or 80% vascular stenoses, and the results of the wavelet transformations. In all analysis results, the top row shows the simulated shunt murmur signal (vertical axis: signal amplitude [mV]; horizontal axis: time [ms]), and the bottom row shows the results of wavelet transformation of simulated shunt murmur signals in the top row (vertical axis: frequency [Hz]; horizontal axis: time [ms]). The color mapping in the images in the bottom row showing the wavelet transformation results denotes the magnitude of the amplitude spectrum for each frequency component, increasing from blue to red. In the AVF models we created, the process was reproduced whereby when the stenosis rate was low, a low-frequency component formed the main component of the simulated shunt murmur, but as the stenosis rate increased, the main component changed to a high-frequency component. ***Figure 2*** also shows flow volumes within the circuit when simulated shunt murmurs were measured for each stenosis rate and calculated values of the normalized cross-correlation coefficient R. In particular, at between 40% and 60% stenosis, intracircuit flow volume started to decrease in association with a reduction in amplitude of the simulated shunt murmur signal, with intracircuit flow volume decreasing as stenosis increased. Along with these changes, R tended to decrease as the stenosis rate increased.

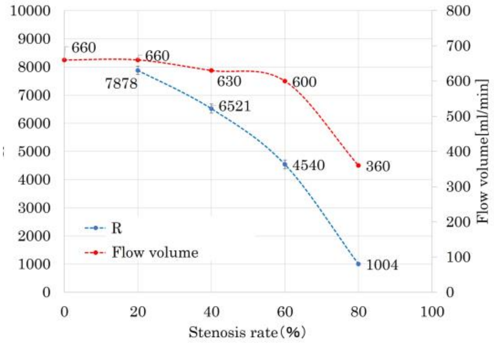
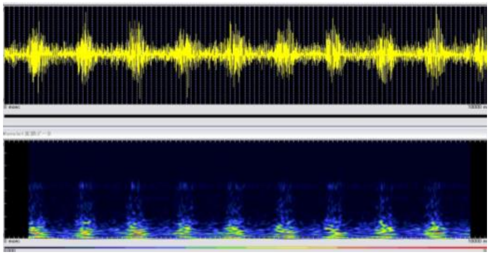
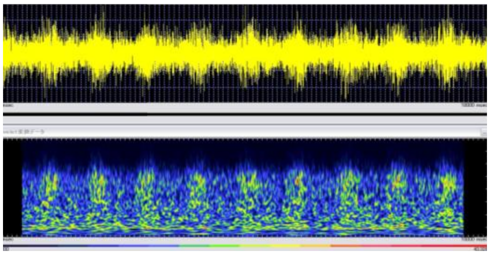


***Fig.2*** R and flow volume measured for each stenosis rate

***Figure 3*** shows the simulated shunt murmur signals measured in AVF models with 20-mm-long 20% or 80% stenosis, and the results of wavelet transformation. ***Figure 4*** also shows the values of the normalized cross-correlation coefficient R calculated from the simulated shunt murmurs measured at each rate of stenosis. With a 20-mm-long stenosis, the process was also reproduced whereby when the stenosis rate was low, a low-frequency component formed the main component of the simulated shunt murmur, but as the stenosis rate increased, the main component changed to a



**(a)** stenosis rate: 20 %



**(b)** stenosis rate: 80 %

***Fig.3*** Simulated shunt murmur signals and results of wavelet transformations (20-mm-long)

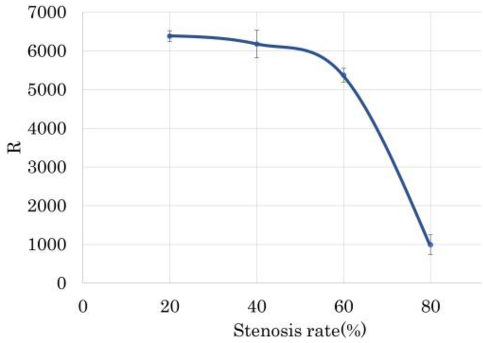
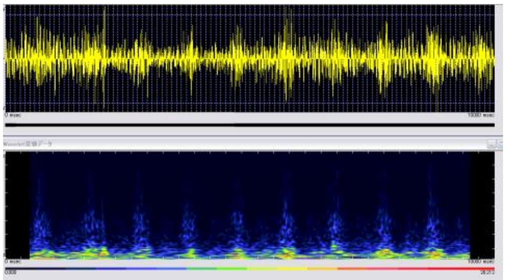
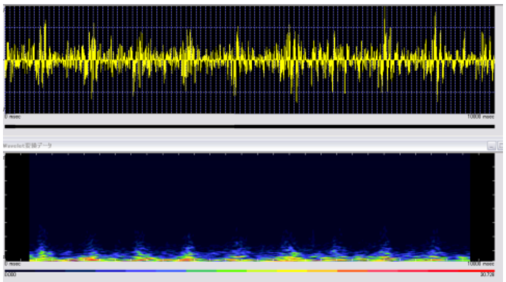


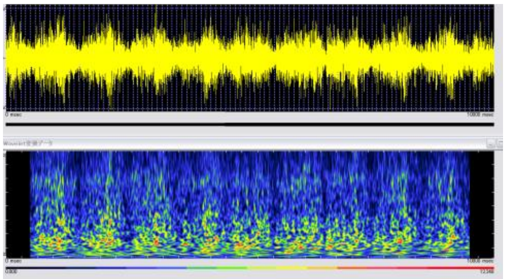
***Fig.4*** R measured for each stenosis rate



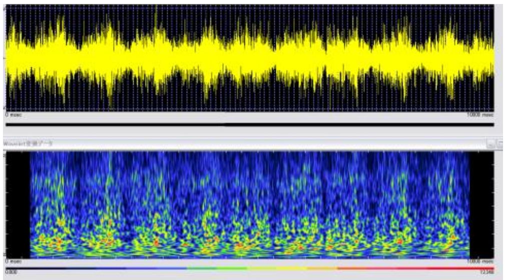
**(a)** The results of analysis for measurements made midway between the stenoses (stenosis rate: 20 %)



**(b)** The results of analysis for measurements 5 mm from the downstream stenosis (stenosis rate: 20 %)



**(c)** The results of analysis for measurements made midway between the stenoses (stenosis rate: 80 %)



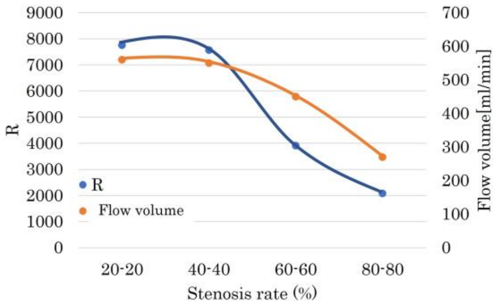
**(d)** The results of analysis for measurements 5 mm from the downstream stenosis (stenosis rate: 80 %)

***Fig.5*** Simulated shunt murmurs in AVF models with multiple stenotic lesions

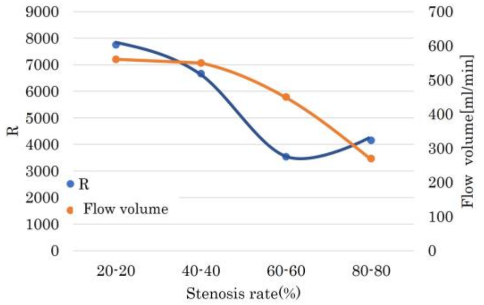
high-frequency component. Compared with the 10-mm-long stenosis, however, R decreased to a greater extent as the stenosis rate increased, indicating that not only the stenosis rate, but also the stenosis length may have major effects on the acoustic characteristics of shunt murmurs.

### 3-2. R values calculated from simulated shunt murmurs in AVF models with multiple stenotic lesions

***Figure 5*** shows simulated shunt murmur signals measured in the AVF models with simulated multiple stenotic lesions of 20% or 80% stenosis, and the results of the wavelet transformation. ***Figure 6*** shows flow volumes within the circuit when simulated shunt murmurs were measured for each stenosis rate, along with calculated values of the normalized cross-correlation coefficient R. The results of analysis for measurements made midway between the stenoses showed that when the stenosis rate was low, a low-frequency compo-



**(a)** between the stenoses



**(b)** 5 mm from the downstream stenosis

***Fig.6*** R and flow volume measured for each stenosis rate nent formed the main component of the simulated shunt murmur, but as the stenosis rate increased, the main component changed to a high-frequency component. Compared with the results of analysis of simulated shunt murmurs measured midway between stenoses, for those measured 5 mm from the downstream stenosis both a mid-frequency component and a low-frequency component were detected. The value of R decreased as the stenosis rate increased, but at 80% stenosis, its value increased at the downstream stenosis site. From these results, the high-frequency component was attenuated when multiple stenotic lesions were present and the mid- and low-frequency components tended to increase. The acoustic characteristics of shunt murmurs may thus differ if different numbers of stenoses are present, and this may also affect the value of R.

## IV. Discussion

In AVF models with graduated stenosis rates simulating VA stenosis, intracircuit flow volume decreased as the stenosis rate increased. The main frequency component of simulated shunt murmurs measured in AVF models changed from a low-frequency component to a high-frequency component, and the normalized cross-correlation coefficient R, which expresses the concordance between color mapping images after wavelet transformation, decreased. However, in real life, some hemodialysis patients show two or more stenotic lesions in the VA. In such cases, the flow of blood between these stenoses will be greatly affected by the lengths and intervening distance, even if stenosis rates are the same. When two stenoses are located close to each other, as in our experiment, the high-frequency component is attenuated and the mid-frequency component increases compared with when a single stenosis is present. This may be because the flow of blood is impeded by downstream stenosis, causing immediate accumulation in front of this stenosis. Compared with the results of analysis for simulated shunt murmurs measured midway between the stenoses, those measured 5 mm from the downstream stenosis showed both a mid-frequency component and a low-frequency component, The value of R at the downstream stenosis site was also increased at 80% stenosis. This may have been because the flow volume was 90 ml/min lower compared with that for a single lesion of 80% stenosis, suggesting that differences in the number of stenoses may affect changes in shunt murmurs. We found that whether a single stenosis or multiple stenoses were present, the value of R and intracircuit flow volume both changed markedly between 40% and 60% stenosis. A stenosis rate of 50% is intermediate between no stenosis (0% stenosis) and complete occlusion (100% stenosis), and clinically can be considered to represent an intermediate state in the progression of stenosis. Our results showed that during this intermediate process, when the shunt murmur changes from low pitch to high pitch as stenosis progresses, reproducing the state in which a mixed shunt murmur including both low- and high-frequency components is audible on auscultation may be possible, allowing calculation of a cut-off value for R at this stenosis rate.

## V. Conclusions

The method we propose in this paper offers the advantage that the R value can easily be calculated in a short time by recording the shunt murmur with an electronic stethoscope or similar device, allowing easy implementation without much trouble, labor, or time. If a clear cut-off value of R could be ascertained, this method could be used to screen for stenotic lesions, and if the value fell below the cut-off, an overall decision could be made in conjunction with other physical findings to promptly proceed to further surveillance-based investigations such as ultrasonography or angiography. This would enable identification of VA dysfunction at an early stage while the stenosis is still mild, which would contribute to VA management by percutaneous transluminal angioplasty (PTA), with the goal of long-term VA patency.

**[Notes]**

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