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Vascular sound visualization system is useful for monitoring and surveillance of vascular access

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Abstract

Backgrounds: Vascular access (VA) is a lifeline for maintenance hemodialysis patients. Monitoring and surveillance of VA, therefore, play an important role for maintaining VA patency. Surveillance needs special apparatus to estimate the VA function, while, monitoring including physical examination does not usually need such devices but highly skill-dependent and qualitative.

Purpose: We report the clinical utility in monitoring and surveillance of VA using a newly developed electronic stethoscope and vascular sound visualization application.

Methods: One hundred eight patients participated in the study. The vascular sounds were collected using the electronic stethoscope, converted into digital data, sent wirelessly to a personal computer, and then calculated. The units for the calculated intensity of the vascular sound were decibel [dB]. The intensity, however, was normalized as INDEX values ranging from 0 to 99 for practical use. Correlation between INDEX and the mean flow volume (mFV) and resistance index (RI) of brachial artery measured by Doppler ultrasound sonography were examined for VA surveillance. INDEX was continually measured at each dialysis session in ten patients who underwent the angioplasty for VA monitoring.

Results: INDEX significantly correlated with the mFV (coefficient of correlation value = 0.68, $p < 0.001$) and RI (coefficient of correlation value = −0.51, $p < 0.001$) of brachial artery. Using the calculated cut-off values, the accuracy of INDEX for the diagnosis of AVF dysfunction ranged from 66% to 82%. INDEX attained the peak just after the angioplasty of culprit lesions and gradually decreased from one patient to another.

Conclusion: These results suggest that vascular sound visualization system can be useful in VA monitoring and surveillance for detecting and predicting the access stenosis.

Keywords

Access monitoring and surveillance, arteriovenous fistula, vascular sound, electronic stethoscope, Doppler ultrasound

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Introduction

Maintaining the function of vascular access (VA) is essential to continue an appropriate hemodialysis treatment and proper vascular access monitoring and surveillance play an important role. Routine physical examination with devices such as inspection, palpation, and auscultation are recommended for vascular access monitoring.[1–4] Clinical practice guidelines recommend imaging examination with such as ultrasound sonography (US) to diagnose a stenosis when abnormal findings are recognized by physical examination.[5–8] US has been commonly used for evaluating the morphology of the access vessels and also for assessing the VA function.[9–11] However, US is expensive, needs skillful technique to operate and make diagnoses, and is not readily used for most dialysis staff. On the other hand, physical examination is routinely performed by any dialysis care givers. Some reports demonstrate that physical examination can accurately detect and localize stenoses in a great majority of arteriovenous fistulas.[1,12,13] Unfortunately, physical examination depends on the

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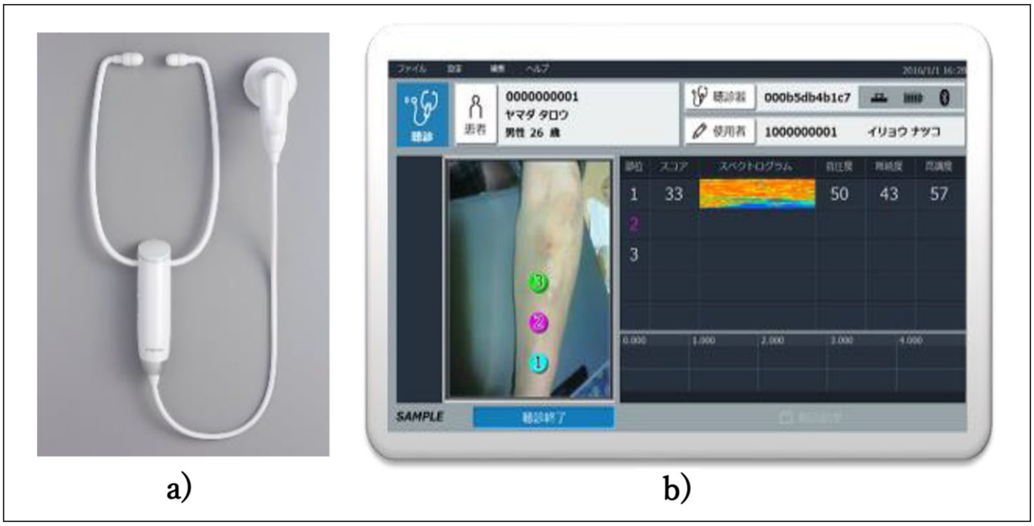

Figure 1. An electronic stethoscope (U10 series (a)) and the vascular sound visualization application (b) for analysis and numeric conversion of vascular sound.

skillfulness or the subjective sense of the examiners. That means physical examinations lack objective numerical values. It is empirically known that vascular sound changes in accordance with the development of access stenosis, however, its changes have not been applied to vascular access monitoring because we did not have devices to save them objectively and efficiently.

Up to now, there were a few reports that attempted to evaluate the vascular access stenosis using stethoscope auscultation,[14–17] however, no reports are found that such equipment are widely used in everyday clinical practice. Pioneer Corporation has recently developed a vascular sound visualization system (VSVS) that can analyze and convert the vascular sound collected by an electronic stethoscope into numerical values. This system consists of an electronic stethoscope and a vascular sound visualization application. When the electronic stethoscope comes into contact with the access vessel, it performs wireless transmission of digitalized vascular sound data to a personal computer. The visualization application installed on the personal computer then immediately converts the vascular sound data received numerical values, which can be displayed and stored.

In this study, we simply focused on auscultation and estimated whether the VSVS is useful for VA monitoring and surveillance with objective numerical values at an ordinary dialysis facility.

Materials and methods

Electronic stethoscope and vascular sound visualization application

Vascular sound collection method. The vascular sound at the arteriovenous fistula was collected using an electronic stethoscope (U10 series; Pioneer Corporation; Figure 1(a), and was converted into digital data, sent wirelessly by Bluetooth® to a personal computer or tablet terminals. The vascular sound at the fistula collected from the patient was evaluated using a special application for analysis and numeric conversion of vascular sound, which has been developed by Pioneer Corporation (Figure 1(b)).

Vascular sound numeric conversion method. Numeric conversion of the vascular sound at the arteriovenous fistula was carried out by the following method. Firstly, the vascular sound was collected using an electronic stethoscope, and was then converted into digital data. From the data sequence obtained, a part of the data for a prespecified short period of time is extracted, and is processed using the short-time Fourier transform (STFT) to obtain the power spectrum. By repeating the above calculation while shifting the time intervals of the signals analyzed, a spectrogram, showing the changes in the power spectrum with time, is obtained for the collected vascular sound at the fistula. STFT is a signal-processing technique that is in general use in the field of signal-processing, including audio signal-processing. Figure 2 shows a sequence of spectrograms of the vascular sound at the fistula before and after percutaneous transluminal angioplasty (PTA), and it can be confirmed that the sound is markedly reduced before PTA, especially during diastole. These findings reflect stasis of diastolic blood flow at the fistula due to stenotic lesions in vascular access.

On the other hand, by defining the unit time and frequency range for the spectrogram, and then obtaining the integrated intensity, the vascular sound at the fistula is numerically converted. The units for the calculated intensity are decibels [dB]. However, with the VSVS used on this occasion, taking into consideration convenience for practical use, the intensity is normalized as INDEX values ranging from 0 to 99.

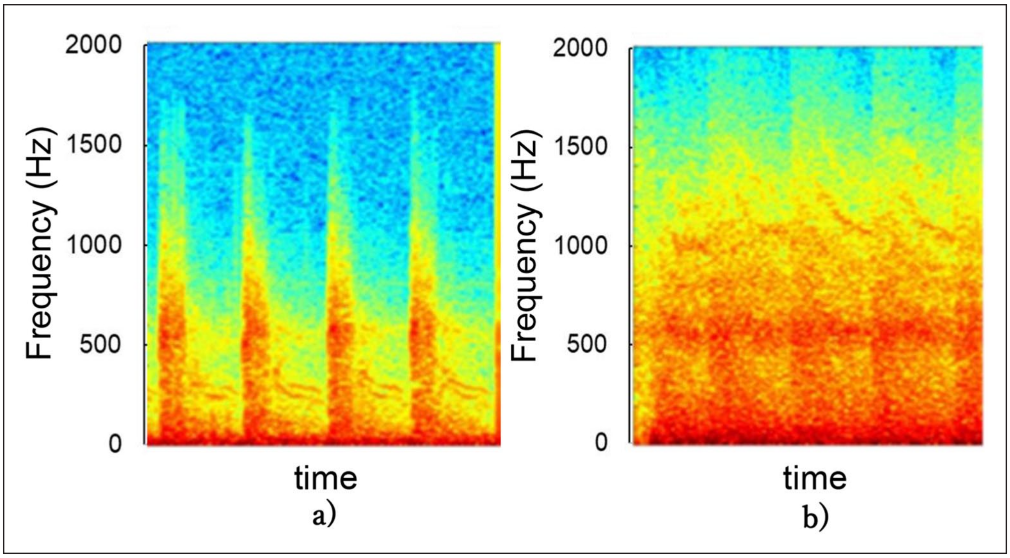

Figure 2. A sequence of spectrograms of the vascular sound at the fistula before (a) and after (b) percutaneous transluminal angioplasty (PTA). The vascular sound is markedly reduced before PTA, especially during diastole.

Vascular sound collection locus. In general, the sound of blood flow at the fistula depends on its vascular shape, and tends to be markedly greater than the sound at other loci. On the other hand, when stenosis develops in the vein proximal to the fistula, and the venous pressure increases, it becomes difficult for blood to flow into the access vein, resulting in decreased vascular sound at the fistula. The vascular sound at the fistula may be expected to reflect the volume of blood flow. We therefore decided to collect the vascular sound at the arteriovenous fistula.

Study patients and study series

Study patients. In this study, 108 outpatients (male: 68, mean age: 70.8 ± 9.5 years, mean dialysis vintage 8.8 ± 5.5 years) undergoing maintenance hemodialysis in our facility were enrolled. Causes of ESRD were as follows: chronic glomerulonephritis 34, diabetic nephropathy 36, nephrosclerosis 18, others 10, unknown 10.

Study series 1. We demonstrated the correlation between INDEX obtained from VSVS and mean flow volume (FVm: mL/min) and Resistance Index (RI) of the brachial artery obtained from ultrasound sonography (US: LOGIQ Book XP (GE Healthcare Japan, Tokyo)). Mean FV calculated using the following formula: FVm (mL/min) = area of the vessel (cm^2) × time averaged velocity mean (TAVM) (m/s) × 60 (s), where area of the vessel is the cross-sectional area of the brachial artery, and TAVM is the mean time integration/heartbeat. RI calculated using the following formula: RI = (PSV-EDV)/PSV, where PSV is the peak velocity in the systolic phase and EDV is the lowest velocity in the diastolic phase. Each patient's data were collected prior to a dialysis treatment at the same day. Auscultation and measurement of FVm and RI were performed by the specialized technicians.

Study series 2. Ten patients who underwent PTA at a certain interval or at the early time of observation period were subjects to the series. Following a guideline issued by Japanese Society for Dialysis Therapy,[8] the indications for PTA are a stenosis of 50% or greater and one or more clinical abnormalities such as decreased blood flow, elevated venous pressure, prolongation of hemostatic time, etc. Vascular sound was collected prior to each dialysis treatment using the electronic stethoscope. Auscultation with the electronic stethoscope was performed by each staff in charge of needling of the dialysis session, not by a certain highly-skilled staff. Changes of INDEX with the passage of time were prospectively followed between August 2017 and June 2018.

Statistics

Spearman's Rank Correlation Coefficient was used to evaluate the correlation between INDEX and FVm or RI. The p less than 0.05 was considered statistically significant. Access blood flow lower than 350 mL/min has been considered as functional deterioration in vascular access.[18,19] We applied the same value for FVm as significant functional reduction. RI higher than 0.6 indicates an existence of stenosis lesion.[19,20] We applied three values 0.6, 0.65, and 0.7 as intrinsic significance for maintaining blood flow. INDEX cutoff values were calculated by receiver operating characteristic (ROC) analysis, respectively, when FVm lower than 350 mL/min was considered positive or when RI higher than 0.6, 0.65, and 0.7 was considered positive. All statistical analyses were performed with EZR (Saitama Medical Center, Jichi Medical University, Saitama, Japan), which is a graphical user interface for R (The R Foundation for Statistical Computing, Vienna, Austria).[21] More precisely, it is a modified version of R commander designed to add statistical functions frequently used in biostatistics.

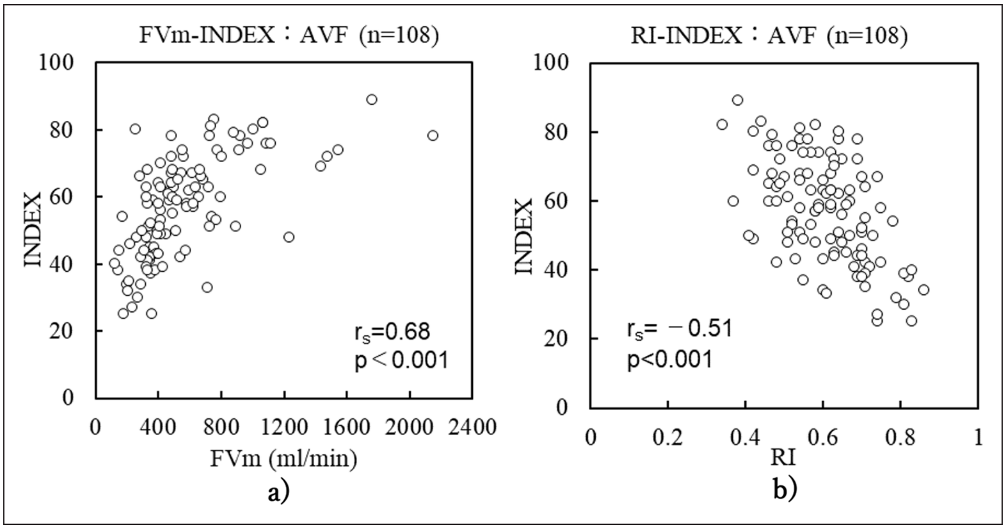

Figure 3. Correlation between mean flow volume (FVm) of the brachial artery and INDEX (a) and correlation between resistance index (RI) of the brachial artery and INDEX (b).

Study results

Study series 1

Figure 3(a) shows the significant positive correlation between mean flow volume (FVm) and INDEX (coefficient of correlation value = 0.68, $p < 0.001$). When FVm cut-off value was configured 350 mL/min, INDEX cutoff value was calculated 48 by ROC curve: points on curve closest to the (0,1) (Figure 4(a)). Using this INDEX cut-off value 48, the accuracy of INDEX for the diagnosis of AVF dysfunction was calculated 82%, with sensitivity and specificity of 70% and 86%, respectively (Table 1.).

Figure 3(b) shows the significant negative correlation between RI and INDEX (coefficient of correlation value = −0.51, $p < 0.001$). When RI cut-off value was configured 0.6 (Figure 4(b)), 0.65 (Figure 4(c)), and 0.7 (Figure 4(d)), INDEX cut-off value was calculated 46, 56, and 55 by ROC curve: points on curve closest to the (0,1), respectively. Using these INDEX cut-off values 46, 56, and 55, the accuracy of INDEX for the diagnosis of stenosis of AVF was calculated 66%, 72%, and 72%, with sensitivity of 43%, 74%, and 85% and specificity of 94%, 71%, and 68%, respectively (Table 1).

Study series 2

Figure 5 shows trend graphs of INDEX collected before each dialysis session. Figure 5(a)–(d) show representative cases repeatedly treated by PTA in a certain span of time. INDEX reached the peak just after the PTA and gradually decreased till the next PTA. Figure 5(e) and (f) show trend graphs of INDEX of the patients treated by PTA once early in the observational course. Time course of the decrease in INDEX of these patients was slow as compared with that of the patients whose access needed repeated PTA in a short period of time.

Discussion

Hemodialysis access is the life line for maintenance dialysis patients. Monitoring and surveillance are key to detect access dysfunction and to maintain healthy vascular access with a timely intervention. The NKF KDOQI Clinical Practice Guidelines 2006 Update for vascular access defined the terms of monitoring and surveillance of vascular access. Monitoring refers to the evaluation of the vascular access by means of physical examination to detect physical signs that suggest the presence of dysfunction. Surveillance refers to the periodic evaluation of the vascular access by means of tests, which may involve special instrumentation and for which an abnormal test result suggests the presence of dysfunction.[22]

Physical examination as clinical monitoring can accurately detect and localize stenoses in a great majority of arteriovenous fistula when it is performed by an experienced interventional nephrologist[1] and even by a renal fellow if trained properly.[13] Other study also showed that the accuracy of physical examination for the diagnosis of AVF stenosis confirmed by Doppler ultrasound was 86%, with sensitivity and specificity of 96% and 76%, respectively,[12] and was 77%, with sensitivity and specificity of 82% and 67%, respectively.[23]

Duplex ultrasound is used for vascular access functional surveillance to provide measurement of access volume flow from the brachial artery,[11,24–26] in addition to anatomical findings.[27,28] It is highly sensitive and specific in detecting stenotic lesions. Accuracy of Doppler Ultrasound is extremely close to angiography in diagnosis of stenosis of vascular

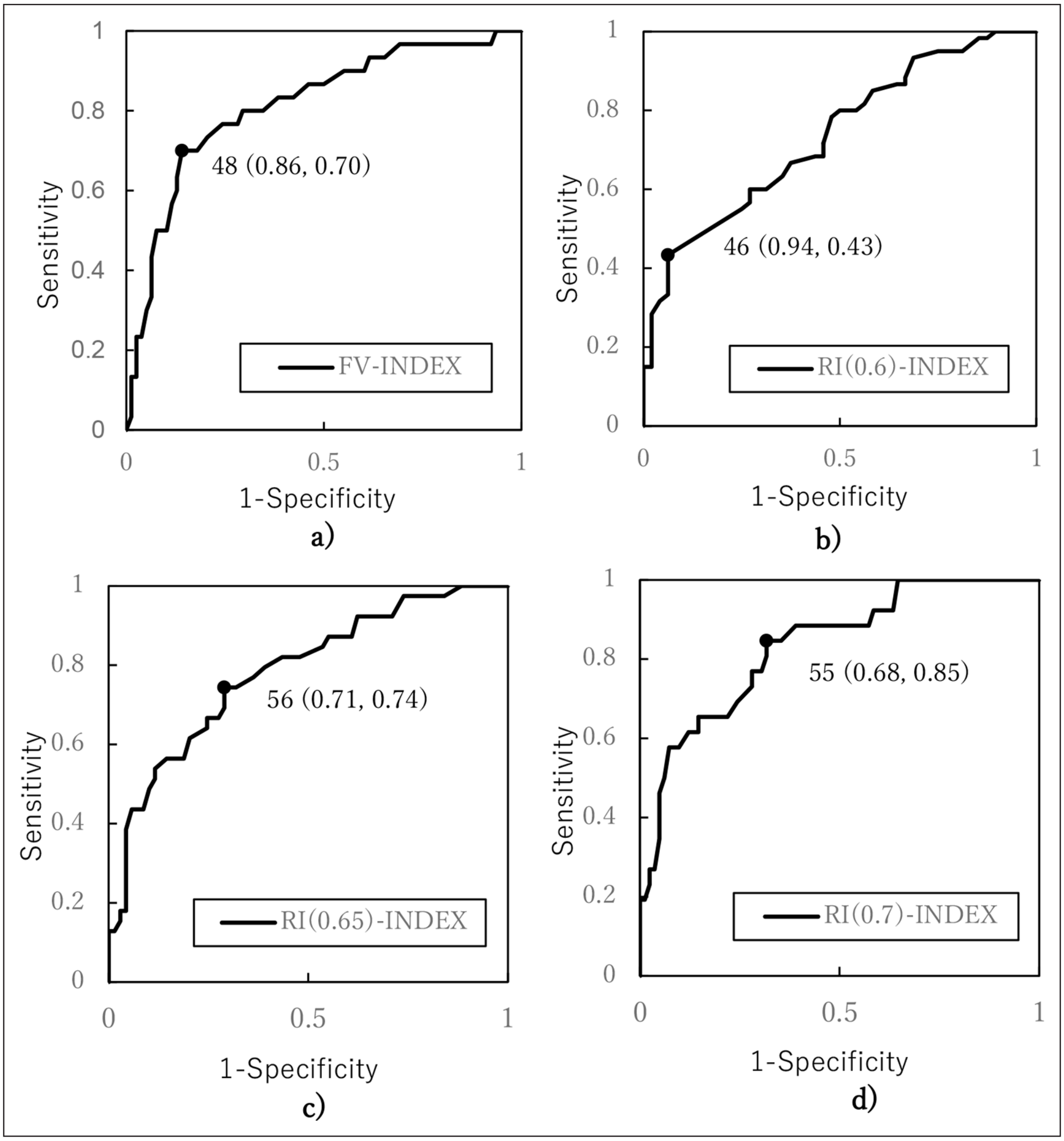

Figure 4. Receiver operating characteristic (ROC) curves as a predictor of significant vascular access stenosis. When FVm Cut-off value was configured 350 mL/min (a), INDEX cutoff value was calculated 48 by ROC curve: points on curve closest to the (0,1). When RI cut-off value was configured 0.6 (b), 0.65 (c) and 0.7 (d), INDEX cut-off value was calculated 46, 56, and 55 by ROC curve: points on curve closest to the (0,1), respectively.

Table 1. INDEX cutoff values and diagnostic accuracy under each conditoin of mean flow volume (FVm) and resistance index (RI).

	Cut-off value	Accuracy (%)	Sensitivity (%)	Specificity (%)
FVm: 350 mL/min	48	82	70	82
RI: 0.6	46	66	43	94
RI: 0.65	56	72	74	71
RI: 0.7	55	72	85	68

access.[9] Moreover, Duplex ultrasound evaluation of arteriovenous fistulas is a simple method to predict the risks of thrombosis and dysfunction when it is used more proactively.[29] Ultrasound sonography is, however, expensive and requires trained ultrasound professionals. Therefore, in the current status, US is still a surveillance tool or a special instrument for detecting access dysfunction and culprit stenoses in ordinary dialysis facilities. On the other hands, electronic stethoscope and Vascular Sound Visualization Application reported in this study is easy to use by any dialysis care givers as part of physical examination and also can be monitoring tool with objective evaluation.

There were a few reports that attempted to evaluate the vascular access stenosis using stethoscope auscultation.[14–17] Among them, Wang et al. showed that by using the technique

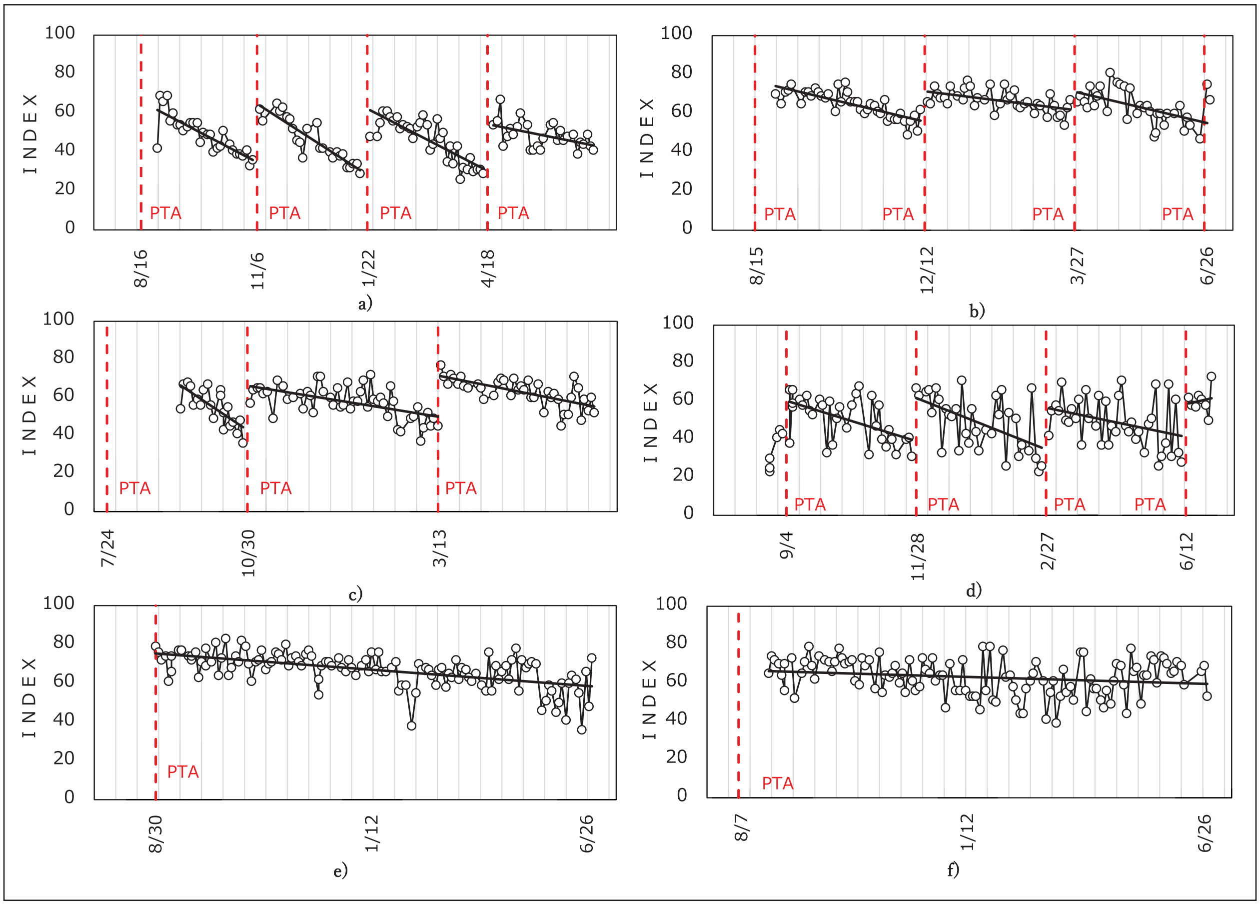

Figure 5. Trend graphs of INDEX collected prior to each dialysis session in six representative cases. (a) to (d) indicate cases repeatedly treated by PTA in a certain span of time and (e) and (f) indicate cases treated by PTA once early in the observation course. PTA means percutaneous transluminal angioplasty. Horizontal axis label is date.

of S-transform, the feature pattern of blood flow sounds for the normal and stenosis states can be effectively extracted and discriminated. And they showed that their proposed AVF stenosis detecting algorithm can provide efficiency for identifying the stenosis of AVF from blood flow sound analysis.[14] By their technique, blood flow sounds can be recognized as the morphological patterns. VSVS proposed in this study, however, transforms blood flow sounds into intensity values, INDEX. INDEX is easier to understand and to save as routine clinical data.

The INDEX obtained from VSVS significantly correlated with the mean flow volume and resistance index of brachial artery measured by Doppler US. It indicates VSVS could be used as a substitute for ultrasound sonography to assess the vascular access function. However, meanwhile, the sensitivity of diagnosis of the stenosis was relatively low as 72% to 82%. It was speculated that there were very few cases of lower than 350 mL/min of access flow volume nor higher than 0.7 of resistance index because pre-emptive PTAs were routinely performed under the surveillance of US in our facility. This study was preliminary. A second generation electronic stethoscope has been developing by Pioneer Corporation. The electronic stethoscope "U10 series" is a device for research and has not been sold. A development of the electronic stethoscope focused on the hemodialysis vascular access sound would be more useful as a monitoring tool with surveillance function in the real world of the vascular access management.

In order to increase the correlation with blood flow volume, INDEX presented by the VSVS is obtained by integrating and calculating the sound intensity restricted to a specified low-pitch range. This is because, even though the blood flow volume is low, the presence of venous valves, etc., sometimes leads to generation of major high-pitched sounds. Therefore, calculation of INDEX with high-pitched components eliminated can increase the correlation with blood flow volume, so that INDEX is not affected by generation of high-pitched sounds. This INDEX can be calculated from the sound at a single heartbeat, but, in order to increase the precision of INDEX, it is preferable to collect data from the sounds during at least five heartbeats, and to calculate the mean.

Figure 5 shows just after PTA of the significant stenosis, INDEX rises to the peak and then gradually decreases. These longitudinal data indicate that the restenosis could progress gradually and the rate of progression of the restenosis may differ from one patient to another. It means that time-dependent changes of INDEX enable us to evaluate the function of the vascular access as well as the rate of progression of the restenosis after the PTA and can be useful to decide when to perform timely intervention. Unfortunately, some trend graphs of INDEX obtained from VSVS displayed considerable fluctuation as seen in Figure 5(d). The cause of this fluctuation was unclear. It may speculate that one was difference in approach methods among examiners such as touch pressure of the stethoscope, a point of auscultation, and an angle of contacting surface of the stethoscope and the other was patients' matter such as changes in blood pressure and changes in increase in body weight. There was a tendency that the influence of technical variations among examiners on INDEX diminished in the fistulas that had juxta-anastomotic aneurysmal changes with venous sclerosis. Physical examinations including auscultation with a stethoscope do play an important role of VA monitoring, and in order to minimize the intra-individual differences, dialysis staffs should be adequately taught how to handle the electronic stethoscope and the application.

More objective monitoring can be performed with digitalization of the vascular sound of each dialysis session, accumulated data of auscultation, and careful observation of the change in INDEX (Figure 5). In addition, VSVS can be useful in assessment of the indication of PTA, reciprocal data-sharing among dialysis caregivers and trend graphs collected at each dialysis session could be powerful tool to explain how well the patient's access is functioning.

Conclusion

Vascular Sound Visualization System with the electronic stethoscope can be useful in vascular access monitoring and surveillance for detecting and predicting the access stenosis. Further studies will be warranted.

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Declaration of conflicting interests

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Ethical approval

Ethical approval was granted by the institutional research committee and informed consent was obtained from all individual participants included in the study.

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References

1. Asif A, Leon C, Orozco-Vargas LC, et al. Accuracy of physical examination in the detection of arteriovenous fistula stenosis. *Clin J Am Soc Nephrol* 2007; 2(6): 1191–1194.
2. Salman L and Beathard GA. Interventional nephrology: physical examination as a tool for surveillance for the hemodialysis arteriovenous access. *Clin J Am Soc Nephrol* 2013; 8(7): 1220–1227.
3. Tessitore N, Bedogna V, Verlato G, et al. Clinical access assessment. *J Vasc Access* 2014; 15(7 Suppl): S20–S27.
4. Koirala N, Anvari E and McLennan G. Monitoring and surveillance of hemodialysis access. *Semin Intervent Radiol* 2016; 33(1): 25–30.
5. Tordoir J, Canaud B, Haage P, et al. EBPG on vascular access. *Nephrol Dial Transplant* 2007; 22(Suppl 2): ii88–117.
6. Sidawy A, Spergel LM, Besarab A, et al. The Society for Vascular Surgery: clinical practice guidelines for the surgical placement and maintenance of arteriovenous hemodialysis access. *J Vasc Surg* 2008; 48(5 suppl): 2S–25S.
7. Gornik HL, Gerhard-Herman MD, Misra S, et al. ACCF/ACR/AIUM/ASE/IAC/ SCAI/SCVS/SIR/SVM/SVS/SVU 2013 appropriate use criteria for peripheral vascular ultrasound and physiological testing part II: testing for venous disease and evaluation of hemodialysis access: a report of the american college of cardiology foundation appropriate use criteria task force. *J Am Coll Cardiol* 2013; 62(7): 649–665.
8. Kukita K, Ohira S, Amano I, et al. 2011 update Japanese Society for dialysis therapy guidelines of vascular access construction and repair for chronic hemodialysis. *Ther Apher Dial* 2015; 19(Suppl 1): 1–39.
9. Doelman C, Duijm L EM, Liem YS, et al. Stenosis detection in failing hemodialysis access fistulas and grafts: comparison of color Doppler ultrasonography, contrast-enhanced magnetic resonance angiography, and digital subtraction angiography. *J Vasc Surg* 2005; 42(4): 739–746.
10. Kudlicka J, Kavan J, Tuka V, et al. More precise diagnosis of access stenosis: ultrasonography versus angiography. *J Vasc Access* 2012; 13(3): 310–314.
11. Mudoni A, Caccetta F, Caroppo M, et al. Echo color Doppler ultrasound: a valuable diagnostic tool in the assessment of arteriovenous fistula in hemodialysis patients. *J Vasc Access* 2016; 17(5): 446–452.
12. Campos RP, Chula DC, Perreto S, et al. Accuracy of physical examination and intra-access pressure in the detection of stenosis in hemodialysis arteriovenous fistula. *Semin Dial* 2008; 21(3): 269–273.
13. Leon C and Asif A. Physical examination of arteriovenous fistulae by a renal fellow: does it compare favorably to an experienced interventionalist? *Semin Dialysis* 2008; 21(6): 557–560.
14. Wang HY, Wu CH, Chen CY, et al. "novel noninvasive approach for detecting arteriovenous fistula stenosis" *IEEE Trans Biomed Eng* 2014; 61(6): 1851–1857.
15. Malindretos P, Liaskos C, Bamidis P, et al. Computer assisted sound analysis of arteriovenous fistula in hemodialysis patients. *Int J Artif Organs* 2014; 37(2): 173–176.
16. Mansy HA, Hoxie SJ, Patel NH, et al. Computerised analysis of auscultatory sounds associated with vascular patency

of haemodialysis access. *Med Biol Eng Comput* 2005; 43(1): 56–62.
17. Kawai M and Suzuki A. Analysis and evaluation of vascular sounds in hemodialysis. *Conf Proc IEEE Eng Med Biol Soc* 2013; 2013: 1017–1020.
18. Tessitore N, Lipari G, Poli A, et al. Can blood flow surveillance and pre-emptive repair of subclinical stenosis prolong the useful life of arteriovenous fistulae? A randomized controlled study. *Nephrol Dial Transplant* 2004; 19(9): 2325–2333.
19. Sato T, Tsuboi M, Onogi T, et al. Standard procedures of endovascular treatment for vascular access stenosis in our facility - clinical usefulness of ultrasonography. *J Vasc Access* 2015; 16(Suppl 10): S34–S37.
20. Tabuchi K, Kobayashi T, Kumagai J, et al. Evaluation of percutaneous transluminal angioplasty screening using color Doppler ultrasonography. *J Vasc Access* 2015; 16(Suppl 10): S53–S57.
21. Kanda Y. Investigation of the freely available easy-to-use software 'EZR' for medical statistics. *Bone Marrow Transplant* 2013; 48(3): 452–458.
22. The NKF KDOQI. Clinical practice guidelines for vascular access. *Am J Kidney Dis* 2006; 48(Suppl 1): S176–S247.
23. Maldonado-Cárceles AB, García-Medina J and Torres-Cantero AM. Performance of physical examination versus ultrasonography to detect stenosis in haemodialysis arteriovenous fistula. *J Vasc Access* 2017; 18(1): 30–34.
24. Bandyk DF. Interpretation of duplex ultrasound dialysis access testing. *Semin Vasc Surg* 2013; 26(2–3): 120–126.
25. Ko SH, Bandyk DF, Hodgkiss-Harlow KD, et al. Estimation of brachial artery volume flow by duplex ultrasound imaging predicts dialysis access maturation. *J Vasc Surg* 2015; 61(6): 1521–1528.
26. Nalesso F, Garzotto F, Muraro E, et al. Standardized protocol for hemodialysis vascular access assessment: the role of ultrasound and color Doppler. *Blood Purif* 2018; 45(1–3): 260–269.
27. Sands JJ, Ferrell LM and Perry MA. The role of color flow Doppler ultrasound in dialysis access. *Semin Nephrol* 2002; 22(3): 195–201.
28. Whittier WL. Surveillance of hemodialysis vascular access. *Semin Intervent Radiol* 2009; 26(2): 130–138.
29. Ishii T, Suzuki Y, Nakayama T, et al. Duplex ultrasound for the prediction of vascular events associated with arteriovenous fistulas in hemodialysis patients. *J Vasc Access* 2016; 17(6): 499–505.