Non-Imaging Acoustical Properties in Monitoring Arteriovenous Hemodialysis Access. A Review

Anas Mohd Noor

Bioinstrumentation Research Lab.,
Biomedical Electronic Engineering, School of Mechatronic Engineering,
Universiti Malaysia Perlis, 02600, Arau, Perlis, Malaysia
Email: anasmohdnoor@gmail.com

Abstract. The limitations of the gold standard angiography technique in arteriovenous access surveillance have opened a gap for researchers to find the best way to monitor this condition with low-cost, non-invasive and continuous bedside monitoring. The phonoangiography technique has been developed prior to these limits. This measurement and monitoring technique, associated with intelligence signal processing, promises better analysis for early detection of hemodialysis access problems, such as stenosis and thrombosis. Some research groups have shown that the phonoangiography technique could identify as many as 20% of vascular diameter changes and also its frequency characteristics due to hemodialysis access problems. The frequency characteristics of these acoustical signals are presented and discussed in detail to understand the association with the stenosis level, blood flows, sensor locations, fundamental frequency bands of normal and abnormal conditions, and also the spectral energy produced. This promising technique could be used in the near future as a tool for pre-diagnosis of arteriovenous access before any further access correction by surgical techniques is required. This paper provides an extensive review of various arteriovenous access monitoring techniques based on non-imaging acoustical properties.

Keywords: *acoustical properties; arteriovenous access; frequency characteristics; hemodialysis; phonoangiography; stenosis; thrombosis.*

1 Introduction

1.1 Arteriovenous Hemodialysis Access and their Relationship to Acoustical Studies

An arteriovenous access (AVA), either an arteriovenous fistula (AVF) or a brachiocephalic fistula (BCF), is an abnormal channel or passage connection between a vein and an artery to allow access to the vascular system for hemodialysis. An AVF is usually located in the forearm and a BCF in the upper arm. There are two types each of AVF and BCF: radiocephalic fistula, arteriovenous graft; brachiocephalic fistula, and brachiobasilic fistula [1]. The

Received April 14th, 2015, Revised October 13th, 2015, Accepted for publication November 13th, 2015.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2015.47.6.6

fistula develops over a period of months after surgery before it can be used for dialysis. This is why a well-functioning AVA is highly important for the patient as a lifeline to a healthy life.

The blood flowing in the arterial and venous system creates a vibration, especially in the fistula and stenosis area. This vibration produces an acoustical wave on its surface (circulatory system) and can be detected at medium surface (the patient's skin) using sound or vibration sensors. This detected signal is categorized by its intensity (amplitude), duration in the time domain, and its frequency spectrum and bands. The physiological artery and venous characteristics such as blood pressure, flow-rate, viscosity, density, resistance, turbulence, and rheology are reflected in the acoustical features, which can be used for detection and measurement. Hence, many research groups are attempting to use these parameters to establish its correlation or relationship to the degree of stenosis severity in hemodialysis patients for early detection before other complicated issues arise.

1.2 The Importance of Arteriovenous Access Monitoring

Before an AVA is created, certain tests and evaluations of the arterial and venous system will be performed on the patient to ensure that the vascular access is able to deliver adequate blood flow at an acceptable rate to support dialysis, while not jeopardizing the viability of the digits and hand. Normally, once a hemodialysis access (HA) has been created, it must develop and mature before it can be utilized. There are two things that critically need to be monitored during the development: the blood flow and the physical characteristics of the AVA. Certain standards are used to determine the maturation and conditions, which takes several days to a month of evaluation. Sometimes, an AVA creates inflow or outflow complications, referring to the cause of the arterial and venous anomalies.

Once the AVA is developed, it needs to be monitored periodically to ensure that the fistula can manage the process of hemodialysis. The main objective is to observe the development and progression of stenoses over time to prevent thrombosis and to avoid any required surgery. The National Kidney Foundation Dialysis Outcomes Quality Initiative (NK-DOQI) has recommended that AVAs must have regular monitoring and assessment. A patient with AVA must take great care to prevent functional failure. The most common failure with fistulas are stenosis, which is an abnormal narrowing of the blood vessel; thrombosis, which is identified as the formation of a blood clot mostly caused by stenosis; and other complications as well. These problems result in a poor blood flow that could reduce the performance and decrease the efficiency of the dialysis process [2]. A venous stenosis generally develops more centrally at areas of vein bifurcation, pressure points and at venous valves. Furthermore, the main cause of these stenoses and thromboses is the continual higher force of blood rushing through the vein and the formation of scar tissue, known as intimal hyperplasia.

It is highly recommended by health experts to monitor the performance and condition of HAs periodically for signs of stenosis or thrombosis [3]. It is highly important that an HA starts functioning within 3 months after its creation. Within this period, it is crucial to determine the condition and performance of the access before it can be used. Currently, two methods are used to monitor the access, invasive and non-invasive techniques. Monitoring and surveillance includes examination and evaluation of the HA to detect the presence of access dysfunction.

1.3 Detection and Analysis

The blood flow vibrations on the AVA produce a unique sound and can be classified into three categories: thrill, bruit and pulse sounds. The NKF Kidney Disease Outcomes Quality Initiative (NKF KDOQI) Clinical Practice Guidelines (2006), produced by the National Kidney Foundation (NKF), suggest that physical examinations such as vision inspection, touching to feel, and listening can be used in monitoring HA conditions.

A healthy AVA thrill sound has a low pitch, is present at anastomosis and along the entire length of the arm during the systolic and diastolic pulse cycle. This in contrast to stenosis, where the thrill only happens in the systolic part and there is loss or absence of thrill along the entire length of arm. The palpation thrill (feel) of normal access is low pulsatile, very soft and compressible whereas an abnormal feel is hard due to high inflow pressure of the arterial. The bruit of a normal AVA condition is also low in pitch and is present in both the systolic and diastolic parts of the pulse cycle along the arm. An abnormal bruit sound, however, is high-pitched, discontinuous and audible and sometimes only available during the systolic part of the cycle [4]. Sometimes, symptoms such as a swelling of the arm or low temperature at the access site may indicate evidence of clotting or poor blood flow. A normal vascular pulse sound is soft, with compressible pulsation generated from cardiac activity. However, the stenosis pulse sound is high intensity and identical to a water hammer effect [5]. The murmur’s intensity relates to the amount of blood flow, while its frequency relates to the vascular diameter. Thus, these sounds can be characterized by their intensity (amplitude), duration in the time domain, and frequency components.

The aim of this work is to review the state of art for monitoring AVA by means of sound. The sound of blood flow running through the HA can potentially help the physician to identify the true condition of the AVA. Currently, the gold standard angiography technique is used in determining the condition of HAs. This conventional method is time-consuming, has a higher operational cost, is invasive and unsuitable for continuous monitoring. Hence, this test is only proposed to critical patients, when it could be too late to detect the problem. Meanwhile, another method for monitoring AVAs is using Doppler ultrasound imaging [6]. The blood flow rate, velocity and vascular diameter are determined and correlated to the level of stenotic severity. This method is also used to predict thrombosis development [7]. In this method, the measurements are represented in an image, which helps the physician to identify the thrombosis condition in the AVA in real-time. Moreover, if the thrombosis is detected sooner, prevention of stenosis could be achieved by percutaneous transluminal angioplasty (PTA). PTA can also be used for visualizing the condition of the AVA by injecting a special dye and allowing a fluoroscope to create an X-ray image, called an angiogram. However, this technique is invasive and only suitable if the stenosis condition is significant and angioplasty is implemented [8]. Hence, it is not suitable for use as periodic access treatment.

Many researchers have reported that the sound signal and its frequency spectra could help to detect any problem in a HA at an early stage. This technique has been identified as phonoangiography, which utilizes acoustical characteristics to analyze the condition of an AVA. Early detection could prolong the access life span and reduce risk of HA failure. The objective of this review is to present the current progress of acoustical studies, their characteristics, such as frequency band(s), and power spectra analysis using a computerized method of artificial intelligence signal processing and classification, which can indicate changes of the signal's pattern prior to stenosis and thrombosis development based on vascular sounds. Furthermore, the relationship between the acoustical signal and the AVA's condition is also be presented.

2 Current Work

In this section, the current HA of AVF and BCF studies using acoustic and digital signal processing techniques are presented. The frequency spectra, energy and band features can be used to identify abnormalities in an HA (stenotic condition), as underlined by many researchers in their studies.

To identify any problems raised or the success of the vascular access, pre-angiography and post-angiography monitoring are recommended. Usually the technique or tool used in this method is a Doppler ultrasound or electronic stethoscope [9-11]. Many agree that the frequency power spectra of stenosis and normal sound are within 0-1000 Hz; it also varies depending on the access stenosis location and its severity. Some studies state that higher frequencies, in the range of 300 Hz and above, correlate with a higher degree of stenosis [11-13].Several analytical techniques have been applied to analyze these acoustic signal features to correlate them with the stages of the stenosis problem. These include root mean square (RMS), true RMS (TRMS), amplitude (A) [11], short-time Fourier transform (STFT) and wavelet transform (WT) [13-15], artificial neural network (ANN) [16], Burg's method [17,18], fuzzy Petri net (FPN), probabilistic neural network (PNN) [12,19], and classifiers such as principal component analysis (PCA) [3], support vector machine (SVM) [3,20], and many others, as summarized in Table 1. They indicated that with these unique frequency features and their characteristics, normal and abnormal vascular sounds can be differentiated. Acoustical sensors, such as a piezoelectric transducer, have mostly been used in the detection of stenosis. The 'electronic stethoscope' [11,14,19,20] is used to auscultate the sound produced and convert this analogue signal to a digital signal for further analysis. Digital signal processing techniques are then used to identify the unique sound of a stenosis, which is mostly a non-periodic signal and very difficult to analyze with regular time-domain or frequency-domain techniques [14,21]. With artificial intelligence techniques, the limitations of these regular techniques are minimized and hence reliable and high-accuracy pre-diagnosis is possible, especially in the early detection of AVA stenosis. Table 1 shows recent clinical acoustical studies of hemodialysis access conditions.

Table 1 Acoustical Studies of Hemodialysis Access.

Researcher	Signal Processing Technique	Finding
Chen, *et al.* [12]	Burg, fuzzy Petri net, autoregressive model	FPN has higher accuracy with dynamic errors, which are used to calculate the frequency spectrum redistribution and potentially show the different degrees of stenosis.
Wang, Y.N., *et al.* [14]	Wavelet transform (WT)	Stenosis features in the 70-800 Hz range are clearly recognized, which indicates that the stenosis affects the high-frequency component in the bloodstream signal with a success rate of 85.54%.
Chen, *et al.* [18]	Burg's method for autoregressive model, fractional-order chaotic system (FOCS)	FOCS can be used to trace the differences in frequency spectra among patients and quantify the variances by dynamic error values, which can be used to estimate the degree of AVS stenosis.
Rousselot, *et al.* [20]	Fast Fourier transform (FFT), Reynolds calculation	The bandwidth of interest was effectively 0-1000 Hz; the energy tended to decrease with increasing frequency. An increase of the severity of the stenosis induces an increase in amplitude.
Gram, *et al.* [21]	Wavelet, T-test statistical analysis	Higher-frequency components developed on stenotic fistula. The positive predictive value was higher than 98%. Significance of $P < 0.000$. It was identified that the frequency ranges of 625-750 Hz and 875-1000 Hz contain a significantly higher percentage of the energy at the stenosis site.

Researcher	Signal Processing Technique	Finding
Wang, *et al.* [22]	2-D feature pattern built from S-transform	Non-stenotic spectra from 200 to 600 Hz compared with stenotic 200-800 Hz, with a positive prediction value over 90% for non-stenotic and 87% for stenotic patients.
Obando, *et al.* [23]	Fourier transform (FT), extended Kalman filter	All subjects with a stenosis problem demonstrated mean sounds in the range 200-600 Hz. Moreover, the amount of sensor pressure on the skin during measurement could affect the results.
Todo, *et al.* [24]	Fourier transform (FT), power spectrum value, T-test statistical analysis	The shunt sounds of the patients with good AVF function (FV, brachial artery) (FV > 500 mL/min or RI < 0.6) are larger in power spectrum values at 51-270 Hz than in patients with poor AVF function (FV < 500 mL/min or RI > 0.6), and the frequency bandwidth for the peak value of the power spectrum is extensive.
Munguia, *et al.* [25]	Power spectral density (PSD) and wavelet transform (WT)	Higher energy and greater mean frequency for a patient with anastomosis. Frequency higher than 200 Hz indicates abnormal AVA.
Munguia, *et al.* [26]	Principal component analysis (PCA), Karhunen-Loeve (KL) features coefficient	The KL coefficient correlates to the stenotic and non-stenotic arteriovenous fistula and can be used to classify the condition.
Sung, *et al.* [27]	Analyzed using a multivariate Gaussian distribution (MGD) model	The relationship of MGD to degree of stenosis (DOS) with 88.89% sensitivity and 83.87% accuracy in predicting the occurrence of stenosis.

Many have reported that acoustical studies benefit in early detection of cases of stenotic AVA. Stenosis reduces the blood flow because of the change in vascular diameter, which becomes narrower and consequently creates high venous pressure that correlates with a higher frequency of the sound signal. Moreover, severe stenosis can lead to thrombosis [24], which could lead to a higher health risk for the hemodialysis patient. Extensive acoustical studies on the AVA issue are taking place. Even though the imaging modalities such as ultrasound and angiography provide significant pre-diagnosis and post-diagnosis of successful HA creation, the ability to provide continuous surveillance is still limited [9,24].

3 Signal Features and Characteristics

3.1 Blood Flow, Sensors Location and Stenotic Severity

Most of the studies demonstrated that significant changes in vascular diameter affect the blood flow-rate [28,29] and change the sound characteristics, which can be identified as higher pitch (frequency) and higher intensity (amplitude) [12,19], and also increase venous pressure [28,30]. A few experimental studies presented different sensor positions or locations for auscultation of the fistula area (arterial and venous side), and showed a limited effect on the sound characteristics. However, some underlined the direct impact on the results of sensor location, skin condition, as well as movement artifacts [13,19,21,31]. The use of digital signal processing techniques in the screening of fistula conditions has led to the development of a decision-making algorithm that allows identifying or classifying the stenosis or thrombosis in early conditions [12,32,33] and may also be used for continuous monitoring compared to imaging techniques [3,11,30]. The classification of AVA sounds is divided into two conditions: non-stenotic or stenotic, although some researchers propose sub-classes of the severity of stenotic cases [18]. Todo, *et al.* analyzed the vascular shunt sound based on a Fourier time-frequency analysis on 50 subjects, and correlated this using two groups of features: brachial artery (FV) blood flow volume and resistance index (RI), to normal and stenotic fistulas. Normal AVF has FV > 500mL/min, RI < 0.6 within a range of 51-270 Hz. On the other hand, a poor AVF has FV < 500 mL/min, RI > 0.6 with a frequency spectrum lower than in a normal AVF patient with a widespread frequency [24]. Mansy, *et al.* [11], Kumbar, *et al.* [30], Nishitani & Inada [31], and Allon & Robbin [34] also confirmed that blood flow is highly correlated with stenosis and thrombosis issues [12,13,20,28] that alter the frequency spectral characteristics.

3.2 Frequency Features and Characteristics

The frequency features of sound signals have been studied by many researchers to create a stenosis and thrombosis classification, as shown in Table 1. Chen, *et al.* demonstrated that the changes in sound intensity and frequency may be correlated with the degree of stenotic severity [12]. They developed an algorithm based on Burg's method, the fractional-order chaos system, and fuzzy Petri net (FPN) for detection of early fistula dysfunction, with three degrees of stenosis: normal, moderate and severe. In this study, a comparison of accuracy between FPN, PNN and SVM resulted in 95% accuracy using the FPN and PNN classifiers compared to SVM, which was 65% accurate.

Wang, *et al.* [22] showed that the positive predictive value (PPV) was more than 87% with a sensitivity of 89% based on 74 cases using s-Transform, 2-D features and a radial basis function (RBF) classifier. They founded that during the critical time of measurement, 0.1-0.3 s, non-stenotic cases showed significant frequencies, ranging from 200-600 Hz, and slowly decayed after 0.3 s. By comparison, the stenotic frequencies were identified in the range of 200-800 Hz and became 600-800 Hz higher after 0.3 s, which suggests a relationship with the cardiac pulse and turbulence at the location of the stenosis. This higher frequency of stenosis (600-800 Hz) was also confirmed by Vesquez, *et al.* [3], who used a wavelet and an SVM classifier; Gram, *et al.* [21], who used a wavelet analysis of eight frequency-band features; and Sato, *et al.* [13], who used a wavelet analysis to identify vascular shunt murmurs. However, none of them have yet established a percentage correlated to the degree of stenosis severity based on their findings, apart from Chen, *et al.* [12].

Other successful algorithms used in the monitoring and detection of vascular stenosis, such as the SVM classifier, have demonstrated a significant difference between normal and abnormal vascular sound. Song [35], who used high peaks from 0-200 Hz and slowly decreased the intensity from 200 to 1000 Hz, and Pablo [3], who used four wavelet decomposition frequencies (6.25-125 Hz, 125-250 Hz, 250-500 Hz, 500-1000 Hz) ranging from 62.5-1000 Hz, have shown that SVM classification (stenotic and non-stenotic cases) sensitivity and selectivity was over 98% in both studies. Nevertheless, they could not establish a correlation with the percentage of the stenosis development, which is an important factor in the early detection and diagnosis of the problem. Only a few studies have indicated that changes in the percentage of the vascular diameter affect stenosis severity [11,12,17].

3.3 Time Amplitude Analysis

Very few researchers have used time-amplitude analysis in determining AVA conditions. With time-amplitude analysis it is hard to determine the features in the stenotic analysis [36]. Mansy, *et al*. [11] conducted an experiment on eleven patients, with before and after angiography results, based on the mean, RMS and TRMS values. The study's purpose was to detect stenosis in the vascular system and to determine the optimum frequency bands and different locations for sensor placement. The authors discovered a clear difference between pre- and post-angiography for a percent diameter change (PDC) > 20%, with intensity differences of more than 10 dB. The mean and RMS spectral differences increased prior to PDC, an outcome which is in contrast with the majority of studies, which demonstrate that higher vascular diameter changes (PDC > 20% in the stenotic vessel) can lead to quieter sounds being produced, as also confirmed by Tessitore, *et al.* [7] and Bosman, *et al*. [37].

In more severe cases, the occlusion that develops has a very low sound and sometimes no sound is produced at all because no or very little blood is flowing [20,28]. Statistical analysis showed that certain parameters correlate well with PDC ($R = 0.98$, $p < 0.001$). Moreover, it has been found that the sensors do not need to be placed exactly over the stenotic vessel for measurement. Similar findings by Sato, *et al.* [13] confirmed that the vessel diameter size affects the tone of the vascular murmurs due to the amount of blood flow and turbulence. However, they also verified that the sounds recorded may vary according to the placement location due to skin and movement artefacts, which contradicts the study by Mansy, *et al.* [11].

3.4 Artificial Stenotic Analysis

Rousselot, *et al.* [20] later demonstrated that stenosis severity (degree of stenosis, DOS) correlated with percentage of vascular diameter varies with blood flow, viscosity, vessel pressure, sound intensity and frequency spectra. However, their study was based on a simulation model and artificial vascular system that mimicked a stenosis condition. They confirmed that the bandwidth of interest in stenotic studies is 0-1000 Hz and the increase of spectral energy intensity is related to the increase of blood flow and velocity. However, when approaching high frequencies, the energy tends to decrease. A similar condition has also been demonstrated by Akay, *et al.* [15] and Mansy, *et al*. [11].

Table 2 Acoustical Study of Hemodialysis Access.

Researcher	Frequency	Normal AVA	Abnormal (Stenosis or Thrombosis)	Result Associated With Frequency Features And Characteristics
Vesquez, *et al.* [3]	0-100 Hz, 60-1000 Hz is selected in the wavelet decomposition	Some subjects showed a measurement frequency of about 400 Hz. Author suggests small steps of frequency analysis to increase accuracy.	Stenotic patients show higher frequency (<1000 Hz)	Energy content in the high-frequency region (lower scale) is high compared to the non-stenotic case. SVM classification shows more than 98% are correlated to stenotic cases and 83% for non-stenotic cases.
Mansy, *et al.* [11]	0-1000 Hz, however the optimum frequency lies between 300 and 600 Hz	Not available. However, energy for normal (< 20% changes of diameter) shows mean, RMS and TRMS values are lower than energy > 20% changes	Spectral energy tends to decrease at higher frequency (300-600 Hz)	The relationship of vascular percent diameter change (PDC) (pre- and post-angiography) shows that the differences of power spectrum are greater for both pre- and post-diameter changes. Significant P-value correlated to vascular percent diameter changes (($r = 0.98$, $p < 0.0001$), larger vascular values contribute to changes of signal density.
Chen, Wei-ling, *et al.* [12]	0-800 Hz	0-150 Hz, 300-380 Hz	150-210 Hz, 300-350 Hz, amplitude peaks at 200 Hz and 350 Hz	Dynamic errors (ψ) are classified to normal, moderate and severity of stenosis percentage. Higher index ψ indicates more severe stenosis.
T. Sato, *et al.* [13]	20-1000 Hz	Not available	400-800 Hz, in three sensor locations	High-frequency sound occurs when the bloodstream is subjected to resistance. 85.54% accuracy compared to the ultrasound result.
Wang, *et al.* [14]	0-1000 Hz	Not available	700-800 Hz	High-frequency sound occurs when the bloodstream is subjected to resistance. 85.54% accuracy compared to the ultrasound result.
Gram, *et al.* [21]	25-1000 Hz	Not available.	625-750 Hz and 875-1000 Hz	Higher-frequency content confirms the stenosis.

Researcher	Frequency	Normal AVA	Abnormal (Stenosis or Thrombosis)	Result Associated With Frequency Features And Characteristics
Todo, *et al.* [24]	20-1000 Hz	41-270 Hz, power spectrum peaks in the range 101-170 Hz	41-270 Hz, power spectrum peaks in the range 111-200 Hz	Lower-power spectrum peaks for group (patients) with poor venous flow (stenotic) compared to normal group, which are higher in the ranges of 41-271 Hz.
Munguia, *et al.* [25]	0-1000 Hz	200-1000 Hz, peak power at 100 Hz	200-1000 Hz, peaks power for anastomosis is lower in low-frequency band	The PSD of the anastomosis recordings showed lower magnitude in the low-frequency band and greater magnitude in the high-frequency band than the reference recordings. Thrill sound also exists at anastomosis site and is hard to differentiate.
Po-Hsun Sung, *et al.* [27]	50-800 Hz	50-450 Hz	< 800 Hz	Higher-frequency components exist due to turbulent flow induced through stenotic region at vascular access.
Grochowina, *et al.* [29]	00-1000 Hz	Averages within 150-250 Hz for 64 cases evaluated	300-700 Hz	Differences between normal and pathological changes in the fistula could be clearly classified in this study using ANN.
Nishitani [31]	8 kHz sampling for recording shunt murmurs	Not available.	250-500 Hz	3 locations (anastomosis, middle and far), studies on initial stage and late-stage stenotic subjects. 250-500 Hz showing high correlation to initial stage of stenosis and position 2 is suitable for recording shunt murmurs (high significance).

The Rousselot model states that when the viscosity is greater, fewer detectable spectral features are found. Differences in viscosity resulted in different spectral bands. The relationship between flows, DOS, pressure before and after stenosis, and velocity parameters clearly shows that flow decreases, whereas DOS, pressure before and after stenosis, and velocity increase. Furthermore, they proved that different DOS percentages resulted in different energy spectra [20]. Borisyuk [38] performed in-vitro studies of the noise produced in artificial vascular stenosis. He also proved that the characteristics of stenosis are the sound intensity and increasing frequency spectra. Furthermore, the frequency peaks are similar to the characteristics of vortex formation at the stenosis area. The acoustic power of the stenosis produced is approximately proportional to the fourth power of the stenosis severity. Table 2 shows the characteristics of AVA murmurs in the acoustical spectra.

4 Conclusions

The monitoring of vascular access is highly important for hemodialysis patients. Even though the imaging technique is important as a tool for further diagnosis of hemodialysis patients, the phonoangiography technique is a dedicated continuous pre-diagnostic tool for early stenotic or thrombosis conditions. Moreover, this technique has a number of advantages compared to the imaging technique: its superiority in terms of management and operational cost, the fact that it is skill-independent, and also its suitability for bed-side screening. Currently, the gold-standard angiography technique is used in HA surveillance. However, concerns with this high-operational-cost, time-consuming and invasive technique have suggested the need to find an alternative method.

With unique signal features in both the time and the frequency domain, researchers have proved that the acoustical technique, in coming years, can be used as a standard procedure before further detailed diagnosis is performed on the patient. Overall, it has been demonstrated that state-of-the-art application of artificial intelligence techniques can help to solve the known limitations. Although researchers have proved that the signal frequency spectra of interest lie within 0-1000 Hz for the vascular signal, there are differences between researchers. Some suggest that higher-frequency spectra energy leads to the stenotic issue, while others find that even low-frequency bands, i.e. < 500 Hz, can still indicate a stenotic condition, but the energy distribution in the spectra differs between a stenotic and a non-stenotic condition, which is interesting to analyze. Numerous artificial intelligence signal-processing algorithms have been applied, although very few of them present side-by-side method comparisons that might point to the best methods and techniques for this application. Furthermore, the research presented and experiments conducted have certain limitations in common, with small groups of subjects making it difficult to strengthen and correlate the degree of stenotic severity with the resulting data.

In addition, physiological conditions, such as the venous-pressure value and blood-flow measurement, should be considered to understand the mechanical properties of the blood, which are not well discussed by the researchers in these studies, and its relationship to stenotic severity. Hence, it is highly recommended to include all these parameters, which provide more reliable analysis. Moreover, the phonoangiography techniques are affected by the measurement location, the size of the sampling window, and sensor sensitivity and selectivity. Even though acoustical analysis is a promising as a diagnostic tool for the future, there are still several aspects, from sensing to analyzing, that need to be improved.

Acknowledgements

This project was partially supported by the Biomedical Integrated Design Project (BIDP), School of Mechatronic Engineering, Unimap. The author would like to thank all staff at Northern Hemodialysis Centre, Changloon, for their support and assistance.

References

[1] Beathard, G.A., *Hemodialysis Arteriovenous Fistulas*, http://www.esrdnetwork.org/assets/pdf/fistula-first/BeathardGuideto AVFs.pdf (30 January 2015).

[2] Mickley, V., *Stenosis And Thrombosis In Haemodialysis Fistulae and Grafts: The Surgeon's Point of View*, Nephrology Dialysis Transplantation, **19**(2), pp. 309-311, 2004.

[3] Vesquez, P.O., Munguía, M.M. & Mandersson, B., *Arteriovenous Fistula Stenosis Detection Using Wavelets and Support Vector Machines*, Engineering in Medicine and Biology Society (EMBC), Annual International Conference of the IEEE, pp. 1298-1301, 2009.

[4] National Kidney Foundation. *NKF-K/DOQI Clinical Practice Guidelines for Hemodialysis Adequacy Kidney*, 2006, https://www.kidney.org/ sites/default/files/docs/12-500210_jag_dcp_guidelines-hd_oct06_sec tiona_ofc.pdf (10 October 2015).

[5] Beathard, G.A., *Physical Examination of the Dialysis Vascular Access, Seminars In Dialysis*, Blackwell Publishing Ltd, **11**(4), pp. 231-236, 1998.

[6] Tonelli, M., James, M., Wiebe, N., Jindal, K., Hemmelgarn, B., & Alberta Kidney Disease Network, *Ultrasound Monitoring to Detect Access Stenosis in Hemodialysis Patients: A Systematic Review*, American Journal of Kidney Diseases, **51**(4), pp. 630-640, 2008.

[7] Tessitore, N., Mansueto, G., Bedogna, V., Lipari, G., Poli, A., Gammaro, L., Baggio, E., Morana, G., Loschiavo, C., Laudon, A., Oldrizzi, L. & Maschio, G., *A Prospective Controlled Trial on Effect of Percutaneous Transluminal Angioplasty on Functioning Arteriovenous Fistulae Survival*, Journal of the American Society of Nephrology, **14(**6), pp. 1623-1627, 2003.

[8] Besarab, A., Asif, A., Roy-Chaudhury, P., Spergel, L.M. & Ravani, P., *The Native Arteriovenous Fistula in 2007 Surveillance and Monitoring*. Journal of Nephrology **20**(6), pp. 656-667, 2007.

[9] Cheng, S-M., Ng, S.-P., Yang, F.-S. & Shih, S.-L., *Interventional Treatment for Complete Occlusion of Arteriovenous Shunt: Our Experience in 39 Cases*, Chin J Radiol, **28**, pp. 137-142, 2003.

[10] Vascular Access 2006 Work Group, *NKF-DOQI Clinical Practice Guidelines for Vascular Access, Update 2006*, Am J Kidney Dis, 48 (Suppl 1), pp. S176-S306, 2006.

[11] Mansy, H.A., Hoxie, S.J., Patel, N.H. & Sandler, R.H., *Computerised Analysis of Auscultatory Sounds Associated with Vascular Patency of Haemodialysis Access*, Medical and Biological Engineering and Computing, **43**(1), pp. 56-62, 2005.

[12] Chen, W.-L., Kan, C.-D. & Lin, C.-H., *Arteriovenous Shunt Stenosis Evaluation Using A Fractional-Order Fuzzy Petri Net Based Screening System for Long-Term Hemodialysis Patients*, Journal of Biomedical Science and Engineering, **7**(5), pp. 258-275, 2014.

[13] Sato, T., Tsuji, K., Kawashima, N., Agishi, T. & Toma, H., *Evaluation of Blood Access Dysfunction Based on A Wavelet Transform Analysis of Shunt Murmurs*, Journal of Artificial Organs, **9**(2), pp. 97-104, 2006.

[14] Wang, Y.-N., Chan, C.-Y. & Chou, S.-J., *The Detection of Arteriovenous Fistula Stenosis for Hemodialysis Based on Wavelet Transform*, International Journal of Advanced Computer Science, **1**(1), pp. 16-22, 2011.

[15] Akay, Y.M, Akay, M., Welkowitz, W., Semmlow, J.L. & Kostis, J.B., *Noninvasive Acoustical Detection of Coronary Artery Disease: A Comparative Study of Signal Processing Methods*, IEEE Transactions on Biomedical Engineering, **40**(6), pp. 571-578, 1993.

[16] Vasquez, P., Marco, M.M., Mattsson, E. & Mandersson, B., *Application of the Empirical Mode Decomposition in the Study of Murmurs From Arteriovenous Fistula Stenosis*, Engineering in Medicine and Biology Society (EMBC), Annual International Conference of the IEEE, pp. 947 - 950, 2010.

[17] Roth, K., Kauppinen, I., Esquef, P.A. & Valimaki, V., *Frequency Warped Bur's Method for AR-Modeling*, IEEE Workshop on Applications of Signal Processing to Audio and Acoustics, pp. 5-8, 2003.

[18] Chen, W.L., Chen, T., Lin, C.H., Chen, P.J., & Kan, C.D., *Phonographic Signal with a Fractional-Order Chaotic System: A Novel and Simple Algorithm for Analyzing Residual Arteriovenous Access Stenosis,*

Medical & Biological Engineering & Computing, **51**(9), pp. 1011-1019, 2013.

[19] Malindretos, P., Liaskos, C., Bamidis, P., Chryssogonidis, I., Lasaridis, A. & Nikolaidis, P., *Computer Assisted Sound Analysis of Arteriovenous Fistula in Hemodialysis Patients*, The International journal of artificial organs, **37**(2), pp. 173-176, 2014.

[20] Rousselot, L., *Acoustical Monitoring of Model System For Vascular Access In Haemodialysis*, PHD dissertation, TU Delft, Delft University of Technology, 2014.

[21] Gram, M., Olesen, J.T., Riis, H.C., Selvaratnam, M., Meyer-Hofmann, H., Pedersen, B.B., Christensen, J.H., Struijk, J. & Schmidt, S.E., *Stenosis Detection Algorithm for Screening of Arteriovenous Fistulae*, 15th Nordic-Baltic Conference on Biomedical Engineering and Medical Physics (NBC), **34**, pp. 241-244, 2011

[22] Wang, HY., Wu, C.H., Chen, C.Y. & Lin, B.S., *Novel Noninvasive Approach for Detecting Arteriovenous Fistula Stenosis*, IEEE Transactions on Biomedical Engineering, **61**(6), pp. 1851-1857, 2014.

[23] Obando, P.V. & Mandersson, B., *Frequency Tracking Of Resonant-Like Sounds from Audio Recordings of Arterio-Venous Fistula Stenosis*, Bioinformatics and Biomedicine Workshops (BIBMW), IEEE International Conference on IEEE, pp. 771-773, 2012.

[24] Todo, A., Kadonaka, T., Yoshioka, M., Ueno, A., Mitani, M., Katsurao, H., Someya, N., Hasegawa, H., Hitomi, Y., Nishigaki, T. & Mizuno-Matsumoto, Y., *Frequency Analysis of Shunt Sounds in the Arteriovenous Fistula on Hemodialysis Patients*, 6th joint International Conference on. Soft Computing and Intelligent Systems (SCIS) and 13th International Symposium on Advanced Intelligent Systems (ISIS), pp. 1113-1118, 2012.

[25] Munguia, M.M. & Mandersson, B., *Analysis of the Vascular Sounds of the Arteriovenous Fistula's Anastomosis*, Engineering in Medicine and Biology Society (EMBC), Annual International Conference of the IEEE, pp. 3784-3787, 2011.

[26] Munguía, M.M., Vásquez, P. & Mandersson, B., *Characterisation of Arteriovenous Fistula’s Sound Recordings Using Principal Component Analysis*, Engineering in Medicine and Biology Society (EMBC), Annual International Conference of the IEEE, pp. 5661-5664, 2009.

[27] Sung, PH., Kan, C.D., Chen, W.L., Jang, L.S. & Wang, J.F., *Hemodialysis Vascular Access Stenosis Detection Using Auditory Spectro-Temporal Features of Phonoangiography*, Medical & Biological engineering & Computing, **53**(5), pp. 393-403, 2015.

[28] Konner, K., Nonnast-Daniel, B. & Ritz, E., *The Arteriovenous Fistula*, Journal of the American Society of Nephrology, **14**(6), pp. 1669-1680, 2003.

[29] Grochowina, M., Leniowska, L. & Dulkiewicz, P., *Application of Artificial Neural Networks for the Diagnosis of the Condition of the Arterio-Venous Fistula on the Basis of Acoustic Signals*, Brain Informatics and Health, pp. 400-411, 2014.

[30] Kumbar, L., Jariatul, K. & Besarab, A., *Surveillance and Monitoring of Dialysis Access*, International Journal of Nephrology, 2012.

[31] Nishitani, Y. & Inada, H., *An Analysis of Frequency Components of Shunt Murmur for Diagnosing Shunt Stenoses in Hemodialysis*, World Congress on Medical Physics and Biomedical Engineering, pp. 196-197, 2009.

[32] Doyle, D.J., Mandell, D.M. & Richardson, R.M., *Monitoring Hemodialysis Vascular Access by Digital Phonoangiography*, Annals of biomedical engineering, **30**(7), pp. 982-982, 2002.

[33] Jing, F., Xuemin, W., Mingshi, W. & Wei, L., *Noninvasive Acoustical Analysis System of Coronary Heart Disease*, Proceedings of the Sixteenth Southern, in Biomedical Engineering Conference, pp. 239-241, 1997.

[34] Allon, M., & Robbin, M.L., *Increasing Arteriovenous Fistulas in Hemodialysis Patients: Problems and Solutions*, Kidney international, **62**(4), pp. 1109-1124, 2002.

[35] Song, W.T. & Chiang, H., *A Novel Approach For Vascular Sounds of Arteriovenous Fistulas and Vascular Stenoses*, http://www.apiems.org/conf2013/conf2013/1292.pdf, (8 Febuary 2015).

[36] Wu, J.X., Du, Y.C., Wu, M.J., Li, C.M., Lin, C.H. & Chen, T., *Multiple-Site Hemodynamic Analysis of Doppler Ultrasound with an Adaptive Color Relation Classifier for Arteriovenous Access Occlusion Evaluation*, The Scientific World Journal, **2014**, Article ID 203148, pp. 1-13, 2014.

[37] Bosman, P.J., Boereboom, F.T., Bakker, C.J., Mali, W.P., Eikelboom, B.C., Blankestijn, P.J. & Koomans, H.A., *Access Flow Measurements in Hemodialysis Patients: In Vivo Validation of an Ultrasound Dilution*

Technique, Journal of the American Society of Nephrology**, 7**(6), pp. 66-969, 1996.

[38] Borisyuk, A.O., *Experimental Study of Noise Produced By Steady Flow through a Simulated Vascular Stenosis*, Journal of Sound and Vibration, **256**(3), pp. 475-498, 2002.