Combined functional and anatomical diagnostic endpoints for assessing arteriovenous fistula dysfunction

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Author contributions: All authors contributed to this work.

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Received: July 14, 2014
Peer-review started: July 19, 2014
First decision: August 14, 2014
Revised: November 7, 2014
Accepted: November 17, 2014
Article in press: November 19, 2014
Published online: February 6, 2015

Abstract

Failure of arteriovenous fistulas (AVF) to mature and thrombosis in matured fistulas have been the major causes of morbidity and mortality in hemodialysis patients. Stenosis, which occurs due to adverse remodeling in AVFs, is one of the major underlying factors under both scenarios. Early diagnosis of a stenosis in an AVF can provide an opportunity to intervene in a timely manner for either assisting the maturation process or avoiding the thrombosis. The goal of surveillance strategies was to supplement the clinical evaluation (i.e., physical examination) of the AVF for better and earlier diagnosis of a developing stenosis. Surveillance strategies were mainly based on measurement of functional hemodynamic endpoints, including blood flow (Qa) to the vascular access and venous access pressure (VAP). As the changes in arterial pressure (MAP) affects the level of VAP, the ratio of VAP to MAP (VAPR = VAP/MAP) was used for diagnosis. A Qa < 400-500 mL/min or a VAPR > 0.55 is considered sign of significant stenosis, which requires immediate intervention. However, due to the complex nature of AVFs, the surveillance strategies have failed to consistently detect stenosis under different scenarios. VAPR has been primarily developed to detect outflow stenosis in arteriovenous grafts, and it hasn't been successful in accurate diagnosis of outflow lesions in AVFs. Similarly, AVFs can maintain relatively high blood flow despite the presence of a significant outflow stenosis and thus, Qa has been found to be a better predictor of only inflow lesions. Similar shortcomings have been reported in the detection of functional severity of coronary stenosis using diagnostic endpoints that were based on either flow or pressure. This limitation has been associated with the fact that both pressure and flow change in the presence of a stenosis and thus, hemodynamic diagnostic endpoints that employ only one of these parameters are inherently prone to inaccuracies. Recent attempts have resulted in development of new diagnostic endpoints that can combine the effects of pressure and flow. These new hemodynamic diagnostic endpoints have shown to be better predictors of functional severity of lesions as compared to either flow or pressure based counterparts. In this review article, we discussed the advantages and limitations of current functional and anatomical diagnostic endpoints in AVFs.

Key words: Arteriovenous fistula; Dysfunctional arteriovenous fistulas; Stenosis; Surveillance; Flow rate;
The accuracy of the current surveillance strategies for detecting a stenosis is debatable, especially in AVFs. These limitations can be associated with specific pathophysiology of AVFs. AVFs can have a significant stenosis and still maintain a relatively high blood flow. In such scenarios, blood flow to AVF gradually reduces over time. Thus, sequential (longitudinal) measurements of Q<sub>v</sub> over time were expected to provide better clinical decision making than a single Q<sub>v</sub> measurement. Also in case of a significant outflow stenosis, the venous access pressure may retain its normal levels at the cannulation site due to development of downstream collateral pathways.

It is noteworthy that similar shortcomings have also been reported in functional (hemodynamic) diagnosis of coronary stenosis. Such diagnostic endpoints for coronary artery disease were either based on pressure or flow; however this neglects the fact that both flow and pressure change in the presence of a stenosis. Recent studies have attempted to shift the current paradigm into introducing new diagnostic endpoints that can account for both pressure and flow variation for assessing the functional severity of a stenosis. This review article describes the advantages and limitations of current surveillance strategies including functional and anatomical diagnostic endpoints in AVFs.

This review has covered the most important and pioneering studies that have reported the use of hemodynamic and anatomical endpoints for assessing the AVF functionality. We performed a literature search using PubMed, Medline, and Google Scholar for studies written in English from 1995 to 2014. We used the following search terms: arteriovenous fistula; surveillance strategies; stenosis; flow rate; pressure; coronary flow reserve; fractional flow reserve; pressure drop coefficient; resistance index, in combination with the exploded term “diagnosis”. The references were included based on their relevance and contribution to address the challenges and future directions in the diagnostic field of stenosis linked to AVF.

AVF MATURATION, FUNCTIONALITY, AND DYSFUNCTION

According to the guidelines of NKF-KDOQI, the venous segment of a matured AVF should follow the rules of sixes: a blood flow > 600 mL/min, a diameter > 6 mm, a depth of around 6 mm, and at least 6 cm of a straight segment for cannulation. Normally, a minimum of 28 d (d: days) should be allowed for AVF maturation before performing the first needling; however, this time could be extended if the AVF fails to mature. Once an AVF is used for cannulation, it should be able to provide a minimum flow rate of 350-450 mL/min during 3–5 h of dialysis without recirculation, a characteristic that defines a functional AVF. A dysfunctional AVF is, however, defined as an access that is not able to provide the minimum flow during dialysis and is clinically identified by variations in thrill/bruit, difficult cannulation, recirculation, excessive bleeding from the venopuncture sites and

Core tip: Current surveillance strategies are based on either flow (Q<sub>f</sub>) or pressure (VAPR) measurements. The Q<sub>f</sub> has only shown to be a good predictor of inflow stenosis in arteriovenous fistulas (AVFs). The VAPR was primarily developed to detect outflow stenosis in arteriovenous grafts and has shown to be a poor predictor of stenosis in AVFs. These limitations have been associated with the fact that both pressure and flow change in the presence of a stenosis and thus, hemodynamic diagnostic endpoints that employ only one of these parameters are inherently prone to inaccuracies. Thus, diagnostic endpoints that can combine both effects of pressure and flow can provide better assessment of stenosis severity in AVFs.

Rajabi-Jaghargh E, Banerjee RK. Combined functional and anatomical diagnostic endpoints for assessing arteriovenous fistula dysfunction. World J Nephrol 2015; 4(1): 6-18 Available from: URL: http://www.wjgnet.com/2220-6124/full/v4/i1/6.htm DOI: http://dx.doi.org/10.5527/wjn.v4.i1.6

INTRODUCTION

Around 600000 Americans have end-stage renal disease, among whom approximately 415000 patients are being treated by hemodialysis through surgically created vascular access (VA). Failure in maintaining a functional VA has been the leading cause of hospitalization in the hemodialysis population and has resulted in more than $1 billion annual cost to the health care system in the United States. The most preferred form of the VA is the arteriovenous fistula (AVF); however, this type of access has still a significantly high failure rate (20% to 50% in the United States). AVF failure requires placement of central venous catheter which is the least desirable form of VA due to its significant morbidity and mortality.

Thrombosis is the major cause of failure in AVFs, which requires endovascular or surgical intervention of the access. The majority of AVFs with thrombosis had an underlying stenosis. A developing stenosis gradually reduces the blood flow to the access and alters the pressure in the AVF. The National Kidney Foundation Kidney Disease Outcomes Quality Initiative (NKF-KDOQI) has recommended routine surveillance to detect the stenosis early enough to allow preemptive interventions. Current surveillance strategies include device-based measurements, such as blood flow to AVF or venous access pressure. Under the current KDOQI guidelines, an AVF with blood flow rate < 400-500 mL/min or a ratio of venous access pressure to main arterial pressure > 0.55 has to be referred to fistulography for assessing the grade and location of the stenosis.

Pressure

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ultimately thrombosis. Thrombosis, the main cause of access failure, is usually preceded by the development of an underlying stenosis. Consequently, the detection of stenosis in AVFs before thrombosis could offer a strategy to improve AVF survival by early intervention.

**Stenosis in vascular access**

Stenosis in vascular access can be categorized into two main groups of inflow and outflow stenoses\(^9,25\). An inflow stenosis is a lesion that occurs around the anastomosis and proximal to the venous needle, while an outflow stenosis is located further from anastomosis and distal to the venous needle. The stenosis location has been shown to be dependent on the type of access. Radio-cephalic AVFs are more prone to inflow stenosis, whereas outflow stenosis is more likely to occur in the brachio-cephalic AVFs. In contrast to AVFs, the arteriovenous grafts (AVGs) mostly develop outflow stenosis\(^26\). Figure 1A\(^27\) and 1B\(^27\) show the schematics of an inflow and outflow stenosis with respect to the anastomosis and cannulation sites, respectively, while Figure 1C\(^25\) shows an angiographic picture of an AVF with multiple inflow and outflow lesions. All the clinical monitoring and surveillance programs have been designed to predict the development of a significant stenosis early enough to allow preemptive corrections of AVFs. Despite the importance of stenosis severity, its definition is still controversial\(^27,28\). A significant stenosis has been defined as a local reduction of > 50% in luminal diameter as compared to the adjacent normal vessel. This definition is inherently biased and is dependent on the location of the reference cross-section in the adjacent normal vessel (Figure 2\(^27\)). Also, imaging techniques such as Doppler ultrasound only provides a 2D illustration of a 3D lesion, while other imaging modalities such as computed tomography (CT)-scan or magnetic resonance imaging (MRI) are expensive and not readily accessible. Despite these drawbacks, the stenosis severity still serves as the most important endpoint to direct the clinical decision making for the timing of further interventions.

**MONITORING AND SURVEILLANCE PROGRAMS**

Monitoring strategies mainly include physical examination (PE) and other clinical evidences of access dysfunction for stenosis detection, while surveillance programs were intended to supplement clinical monitoring by measuring variations in blood flow rate and venous access pressure. The PE, backbone of all screening programs, is a readily available and cost-effective tool to detect inflow and outflow stenosis in AVFs. PE has proved to be an accurate predictor of venous stenosis, and several studies have concluded that PE should be the part of all screening programs\(^29\). The only drawback of PE is the need for
trained and experienced dialysis personals, leading to variability in decision making.

FUNCTIONAL (HEMODYNAMIC) ENDPOINTS

A developing stenosis eventually reduces blood flow and alters pressure profiles in the vascular access. Effects of stenosis on hemodynamic (blood flow and pressure) profiles are dependent on the type of vascular access (AVF or AVG) and the location of stenosis (inflow, outflow, or both). Therefore, monitoring the changes in flow and pressure can provide useful functional information on the severity of the underlying stenosis. NKF-KDOQI guidelines have recommended that both AVGs and AVFs undergo routine surveillance for blood flow and venous access pressure measurements.

Flow surveillance

The blood flow ($Q_f$) measurement is currently the gold standard of all surveillance programs. The $Q_f$ measurement has been shown to be fairly reproducible both within and between the dialysis sessions. Blood flow rate can be measured by either indirect techniques such as ultrasound dilution or direct methods such as Doppler ultrasound, or MRI. The latter can provide valuable information about the location and severity of stenosis; however, it has the disadvantage of being more expensive and time consuming. Figure 2[27,30] shows a sample velocity pulse obtained from Doppler ultrasound as well as an example of detected stenosis using such technique. Although $Q_f$ has been widely used as the most reliable surveillance strategy, there are numerous different $Q_f$ thresholds for clinical decision makings in AVFs[33]. A wide range of $Q_f$ from 300 mL/min to 900 mL/min[32-35] has been reported in different studies as the threshold for intervention. Under current KDOQI guidelines, an AVF should be referred for fistulogram when $Q_f < 400-500$ mL/min.

Polkinghorne et al[15] looked at the effectiveness of the KDOQI guideline for $Q_f$ (< 500 mL/min) to detect a significant stenosis in 137 patients with AVF. These patients were randomly assigned to a control group receiving standard-of-care clinical treatment and $Q_f$ surveillance group that received the same treatment as the control group plus monthly $Q_f$ measurement. Under the normal treatment, an AVF was referred to fistulography if any of the following occurred: (1) raised venous dynamic pressure; (2) reduced blood pump flow; or (3) excessive bleeding from venopuncture site. They showed that the likelihood of stenosis detection in the $Q_f$ surveillance group was two times but insignificant in relation to the control group, with a trend for a significant stenosis to be detected earlier. However, they also showed that over reliance on only blood flow threshold < 500 mL/min could misdiagnose some cases with positive sign of stenosis under standard-of-care treatment and angiography. They concluded that this misdiagnosis could be due to lack of understanding of the relationship between the blood flow in the vascular access and a developing stenosis.

Tessitore et al[33] tested different surveillance techniques such as PE, venous access pressure ratio, recirculation, and $Q_f$ on a random population of 119 matured AVFs to find the ability and accuracy of these methods in detecting a significant stenosis. In addition to the surveillance methods, all patients underwent angiography to identify the grade of stenosis in the AVFs. Almost 50% of the AVFs had a significant stenosis either upstream of venous needle (inflow stenosis) or downstream of venous needle (outflow stenosis) or at both sites. A combination of PE and $Q_f < 650$ mL/min was able to provide a moderate-to-excellent tool to detect inflow stenosis with sensitivity of 85% and specificity of 89%. However, $Q_f$ was not determined to be an adequate predictor of outflow stenosis. Therefore, they concluded that accuracy of $Q_f$ to detect a significant stenosis is strongly dependent on the location of lesion.

Moreover, a randomized study[36] on 58 patients showed that preemptive intervention for AVFs with a $Q_f > 500$ mL/min results in 3-fold reduction in thrombosis and loss of vascular access as compared to the KDOQI guideline ($Q_f < 400-500$ mL/min) that is more suitable to detect a hemodynamically significant stenosis. Therefore, the current $Q_f$ surveillance for AVF needs modification for improved detection of a significant stenosis well before it adversely affects the functional or hemodynamic condition.

Pressure surveillance

Besarab et al[37,38] proposed the use of venous access pressure to predict the stenosis severity in AVGs. Figure 4[38] shows the schematic for the measurement of venous access pressure using pressure transducers at the...
venous needle and also at the drip chamber of dialysis circuit. Further with the development of this technique, the ratio of venous access pressure (VAP) to the mean arterial pressure (MAP) was used for detecting the stenosis severity (VAPR = VAP/MAP). A VAPR > 0.55 was associated with a clinically significant stenosis. In a prospective study, Besarab et al.\[39\] monitored the variation of VAPR on 832 patients among whom 80% of accesses were AVG. The VAPR > 0.55 was found to be an excellent criterion for angiographic referral and intervention of a clinical stenosis in AVGs. It should be noted that VAPR was primarily developed to detect outflow stenosis in AVGs and by design was unable to detect an inflow stenosis\[10\]. It should be noted that AVGs are more prone to develop an outflow stenosis than an inflow lesion. In case of an inflow stenosis pressure drops in the access and consequently, VAPR remains below the cut-off level. Thus VAPR has been unsuccessful to detect the inflow lesions in AVGs.

Although, the VAPR is a promising parameter in AVGs\[13,18,39,40\], it has failed to show much advantage in assessing the functionality of AVFs\[8,9,15\]. This assertion originates from the fact that there is a fundamental difference between AVFs and AVGs. The AVG is essentially a single tube that connects the artery to vein, and thus, all the blood that enters the arterial anastomosis has to exit from the venous anastomosis. Therefore, any abnormal elevation in the pressure can be associated with the formation of stenosis mainly in the outflow segment. In contrast, the VAPR may show lesser variation while a stenosis is developing in an AVF because of the collateral pathways (accessory or collateral veins) that provide an alternative route to bypass the significant stenosis. Consequently, the flow in
the upstream venous segment of AVFs may not change even in the presence of downstream significant stenosis. In other words, the VAPR may undergo minimal changes as the flow can occur due to presence of downstream collateral channels.

The effect of stenosis on the flow and pressure fields is dependent on the location of stenosis. In general, an outflow stenosis causes an increase in the venous access pressure, while the access flow decreases over time. This is particularly more evident in an AVG than an AVF. In such scenario, an AVF can maintain a relatively high flow rate with almost unchanged pressure levels due to the development of collaterals. In the case of an inflow stenosis venous access pressure either remains stable or can decrease with the reduction in access flow under adverse remodeling. Therefore, pressure monitoring alone may not be able to detect such inflow stenosis, while it can be detected by sequential flow measurements and PE.

ANATOMICAL ENDPOINTS

Once an access is diagnosed for a significant stenosis either based on the standard-of-care clinical treatment or any of the functional surveillance strategies, a fistulogram is acquired to determine the grade and location of stenosis. However, as discussed earlier, there are a few criticisms to the current measurement protocol of the stenosis severity based on a fistulogram. These include: (1) fistulogram provides only a 2D illustration of 3D vessel; and (2) stenosis definition is biased to the location of the reference cross-section in the adjacent normal vessel for which the diameter varies a lot.

For example in a recent study, Fahrtash et al.[27] criticized the current definition of stenosis severity and showed that, stenosis can have a wide range of severity from -25% to 75% reduction in luminal diameter based on the location of reference cross-section (Figure 2). Therefore, they hypothesized that a significant stenosis can be determined based on the absolute minimum diameter in the AVFs. They divided 170 radio-cephalic AVFs into two groups: dysfunctional (n = 93) and functional (n = 77) AVFs. The absolute minimum diameters of two groups were measured using grayscale and color ultrasound. They found that a diameter of 2.7 mm can be a good cutoff value to distinguish a functional radio-cephalic AVF from a dysfunctional one. Using multivariate logistic regression analysis, a vein diameter > 4 mm was found to be the only independent predictor of AVF maturation. However, a previous study by Wong et al.[44] on 46 patients with initial radio-cephalic fistula suggested a diameter > 1.6 mm as the predictor of successful maturation of AVF. Therefore, despite its significance, there is still not a uniform agreement on the minimum diameter of AVF that can assist the clinical decision makings.

OTHER FUNCTIONAL ENDPOINTS

In addition to flow, pressure, and anatomical endpoints, wall shear stress has also been shown to have a strong correlation with functionality of AVFs. A multi-fold increase in blood flow rate after the AVF placement results in an extensive raise in the wall shear stress (WSS) levels acting on the luminal surface of the fistula. In order to accommodate for the marked increase in the hemodynamic stresses, the arterial and venous segments of the AVFs undergo structural changes such as vasodilation and wall hypertrophy.[45-48] These compensatory responses, also known as remodeling, attempt to regain the baseline levels of hemodynamic stresses (pre-surgery condition) in the vessels. Arterial remodeling in AVFs is mainly characterized by dilation and intima-media hypertrophy (outward hypertrophic remodeling).[49] However, this adaptive remodeling in the venous segment can be interrupted by aggressive formation of neointimal hyperplasia, which can result in an undesired hypertrophy (thickening of the venous wall in the inward direction) and later venous stenosis, the major cause of failure in the AVFs. Therefore, monitoring the WSS levels can provide useful information on the functionality status of the AVFs.

Rajabi-Jaghargh et al.[50] studied the linkage between the longitudinal changes in WSS and the luminal dilatation of the AVFs in a pig model. Changes in the WSS levels within the AVFs were evaluated from the computational fluid dynamics models of the fistulas that were developed based on the acquired CT-scan and Doppler ultrasound data of the pigs at 2 d, 7 d, and 28 d post surgery time points. It was found that the slope of changes of WSS over time ($\tau' = (WSS_{d+7 d} - WSS_{d})/(time difference)$) can be used to assess the functionality status in AVFs. The $\tau'$ for the AVFs with favorable remodeling (FR), as shown in Figure 5A[50], was negative between all the successive time-points representing a consistent decrease in the WSS levels over time. In contrast, for the AVFs with adverse remodeling (AR), Figure 5A, the $\tau'$ at all the successive time-points were positive showing that WSS levels were
increasing over time for this group. These opposite patterns of WSS over time were accompanied with distinct remodeling behaviors within the two groups. The luminal area of the venous segment for the FR increased over time (Figure 5B), while for the AR the luminal area remained unchanged or reduced.

Also, in another study by the same group, they showed that the temporal changes in shear stress can be correlated with morphological changes in the venous segment (Figure 6A). The morphological changes were quantified by calculating the ratio of differences in luminal diameter of venous segment over time (△Dh) to the corresponding amount of intima-media thickening (IMT). The IMT was calculated from (B) histology analysis using hematoxylin and eosin (H and E). The IMT was calculated as the average of intima-media thicknesses at four quadrants of each H and E staining slide. FR: Favorable remodeling; AR: Adverse remodeling; AVFs: Arteriovenous fistulas. Reprinted from Rajabi-Jagahrgh et al[51], with permission.

Although WSS has a key role on remodeling behavior and functionality of AVFs, the complexities and limitations associated with the accurate calculation of WSS under clinical settings have made it an undesirable clinical endpoint for surveillance strategies. Therefore, the main focus of this review is to introduce new diagnostic tools that can be readily available under current clinical settings such as flow, pressure, and anatomical endpoints. These endpoints, especially flow and pressure, have also been the main focus of surveillance strategies. However, as mentioned earlier the ability of current surveillance strategies to predict the functionality
status of AVFs has been controversial. This limitation can be associated with the fact that $Q_0$ is based on only flow measurements, while the VAPR is a pressure based parameter. However, it may be noted that both flow and pressure change under a developing stenosis. Therefore, relying on parameters that are either based on pressure or flow can result in inaccurate and less than optimal decision making outcomes. Consequently, there is a need for new functional diagnostic endpoints that can combine both effects of pressure and flow.

**FUNCTIONAL DIAGNOSTIC PARAMETERS FOR CARDIOVASCULAR AND RENAL STENOSIS**

Adequacy of diagnostic tools that are based on either pressure or flow has been one of the major challenges for assessing the functional severity of stenosis in vasculatures such as coronary and renal arteries\(^{[52,53]}\). In this section, the limitations of current hemodynamic (pressure or flow) based endpoints for detecting the cardiovascular and renal stenoses will be discussed. Also, the combined functional (pressure and flow) endpoints for better detection of stenosis in vasculatures will be introduced.

**Existing cardiovascular and renal diagnostic endpoints**

Currently, fractional flow reserve (FFR; a pressure ratio) and coronary flow reserve (CFR; a flow ratio) are the two gold standards to assess the functional severity of a stenosis in coronary arteries\(^{[54]}\). FFR is the ratio of mean pressure distal to a stenosis to the mean proximal pressure under hyperemic condition. CFR is the ratio of blood flow rate to a diseased vessel under hyperemic condition to the corresponding basal (non-hyperemic or resting) flow. The values of FFR and CFR decrease as the stenosis severity increases. However, both FFR and CFR are affected not only by the stenosis severity but also by distal microvascular flow resistance that can increase under left ventricle hypertrophy, chronic or acute ischemia, diabetes mellitus, and other disease conditions\(^{[55-57]}\). If microvascular resistance is abnormal (high), then CFR decreases while FFR tends to increase. Under such scenario, FFR may be incorrectly above the cut-off (0.75-0.8) range despite the existence of a significant stenosis\(^{[58,59]}\). This may lead to inaccurate diagnosis which can result in either delay or missing of intervention procedure. Similar limitations exist for current KDOQI surveillance strategies to detect an outflow stenosis. Also, in the presence of collateral channels both CFR and FFR increase which result in uncertainty in diagnostics\(^{[60]}\). This is also similar to the scenario of an outflow stenosis with developed collateral channels in AVFs. These limitations have been associated with the inherent inaccuracies of current diagnostic parameters to detect stenosis severity that are based on either pressure or flow measurements.

Such gap has resulted in recent attempts to introduce better diagnostic tools that can combine the effects of pressure and flow\(^{[61-64]}\). The new diagnostic endpoints rely on fluid dynamics principals that are based on non-linear relationship between pressure and flow in the presence of a developing stenosis.

**Pressure-flow relationship in stenosed vessels**

Based on fluid mechanics fundamentals, pressure drop for an incompressible (blood) flow inside a vessel is a function of frictional forces (viscous losses) and losses due to momentum changes. The latter can be induced by variation in luminal diameter (or area) of the vessel (i.e., as a result of a stenosis), or presence of bends, bifurcations, anastomosis, and, etc. The viscous forces are linear function of flow, while the momentum changes have quadratic (non-linear) relationship with flow. In general, the pressure drop-flow relationship can be written as below:

$$\Delta p = A v + B v^2$$  \(1\)

where $A$ and $B$ represent the coefficients of viscous losses, and losses due to momentum changes, respectively. Equation 1 can be also written in a more general form as below:

$$\Delta p = k v^n$$  \(2\)

where $n$ can vary between 1 and 2. The exponent in this relationship is of specific importance. For a fully developed laminar flow in a straight vessel, viscous losses are the main component of pressure drop. For such flows, $n$ is nearly equal to 1. However, if the momentum of flow changes due to change in luminal diameter (i.e., as a result of a stenosis), or due to existence of bends, bifurcations, or anastomosis, then the exponent of $\Delta p$-$v$ relationship will become greater than 1. As the exponent becomes closer to 2, the contribution of momentum changes to pressure drop become more pronounced.

Using analytical formulations, Rajabi-Jaghargh et al\(^{[65]}\) have shown that at early stages of stenosis, viscous losses are the most dominant component of pressure drop and $n$ stays closer to 1. However, as the stenosis severity increases from 64% to 90% area stenosis the contribution of momentum changes to pressure drop becomes more pronounced and $n$ will be > 1.5. Figure 7\(^{[65]}\) shows the contribution of viscous losses and losses due to momentum changes to the total pressure drop in a stenosed artery with the increase in the percentage area stenosis. The $n$ is equal to 1.5 at the point where the viscous losses and momentum changes contribute equally to the total pressure drop. For $n < 1.5$, the contribution of viscous losses are more, while losses due to momentum changes are more pronounced for $n > 1.5$. In case of an AVF, anastomosis segment imposes a local pressure loss due to momentum changes (blood flow acceleration in the bend), and thus $\Delta p$-$v$ relationship is expected to have an exponent $> 1$. Although the $\Delta p$-$v$ relationship does not directly help us to evaluate the functionality of an AVF, analyzing the exponent of $\Delta p$-$v$...
relationship can identify the contribution of viscous or momentum losses to the total pressure drop and the underlying geometrical variations (diameter or area change) in the AVF.

**COMBINED FUNCTIONAL DIAGNOSTIC ENDPOINTS**

Based on the pressure-flow relationship in stenosed vessels, the new functional diagnostic parameters can be defined as (1) resistance index, which represents the linear scaling of pressure drop with the velocity at the proximal artery \( (R = \Delta p / v) \); and (2) pressure drop coefficient, which is a pressure drop normalized by the dynamic pressure at the proximal artery \( (C_p = \Delta p / (0.5 \rho v^2)) \), where \( \rho \) is blood density. The resistance index would be more helpful to predict a developing stenosis in early stages where \( n \) is closer to 1, while the pressure drop coefficient becomes more important as the stenosis becomes more severe over time in which case \( n \) is closer to 2. Both \( R \) and \( C_p \) have been shown to be better predictors of the functional severity of coronary stenosis under the limiting scenarios (i.e., microvascular disease and collateral channels) as compared to FFR and CFR, the current gold standards[66-69].

**Combined functional diagnostic endpoints in AVFs**

The new functional diagnostic endpoints (resistance index, \( R \), and pressure drop coefficient, \( C_p \)) have been recently[70] used in a pilot study on a pig model. It was shown that these parameters are capable of detecting the very early signs of a developing stenosis in AVFs. In this study, six AVFs were created between the femoral arteries and veins of 3 pigs, each pig having two AVFs on either limb. The variation in flow rates and geometries of the AVFs were studied at three post-surgery time points (2 d, 7 d, and 28 d) over about one month using Doppler ultrasound and CT-scan techniques. Also, computational fluid dynamics were used to calculate the pressure and velocity profiles for all the AVFs at every time point. Time averaged pressure difference between the proximal artery and outflow vein in conjunction with the average velocity at proximal artery were used to calculate \( C_p \) and \( R \) in AVFs. During the first week, all AVFs attained favorable remodeling[50,51] characterized by dilation, significant increase in flow rate, unchanged pressure drop, reduction in severity of local stenosis, and some amount of thickening due to the development of intimal hyperplasia. These changes were associated with the reduction in \( C_p \) and \( R \) levels over the first week (Figure 8).

In contrast, from 7 d to 28 d some of the AVFs showed significant dilation, while others experienced minimal changes in the mean diameter. During this period, the amount of thickening was also doubled in all the AVFs. Therefore, the minimal dilation and high amount of IMT from 7 d to 28 d for some AVFs resulted in adverse remodeling characterized by inward hypertrophy in those AVFs. On the other hand, the AVFs with significant dilation and venous wall thickening underwent positive remodeling with outward hypertrophy. Over this time period (7 d-28 d), the increase in average diameter and flow rate were minimal as compared to the first week, while the pressure drop increased for 50% of its baseline value. Also, the severity of the local stenosis, measured by area reduction, in AVFs (Figure 8A[70]) increased to 41.7% ± 8.3% which was below the clinically significant level (= 75% area stenosis). Corresponding to these changes, \( C_v \) and \( R \) (Figure 8B[70]) increased considerably over this time period. It was concluded that assessing the AVF functionality based on only diameter or flow rate could be misleading because they may not reveal complete information regarding the developing stenosis. However, \( C_v \) and \( R \) significantly increased over this time period and showed better delineation of stenosis severity. Thus, \( C_v \) and \( R \) could better assess the functionality of an AVF. However, this study was limited to relatively small number of data points and thus, studies with larger population and longer duration are needed to better determine advantages of the new combined pressure-flow diagnostic endpoints over the current gold standards.

**Bedside measurement of new functional diagnostic endpoints**

It should be noted that all the pressure-flow parameters that are needed to calculate \( C_v \) or \( R \) can be measured under current clinical settings. Velocity at the proximal artery can be measured through Doppler ultrasound probes and the pressure drop can be measured from the pressure readings at the cannulation sites during
the dialysis treatment. In the case of an inflow stenosis both $R$ and $C_p$ increases as pressure drop increases and flow rate decreases. Thus, both $R$ and $C_p$ are capable of detecting a developing inflow stenosis. If stenosis occurs downstream of the venous cannula (outflow stenosis) in AVFs, the pressure readings can show either lower or unchanged values of pressure drop over time, which does not reflect the presence of downstream stenosis. This is because of the development of collateral channels at the outflow stenosis area in AVFs. This shortcoming has been the major criticism to the current pressure surveillance program in which the AVF patency is assessed based on only pressure ratios at the outflow venous cannula and proximal artery. In such scenarios, if the venous flow rate decreases, both $C_p$ and $R$ begin to increase. It is noteworthy that irrespective of ∆$p$ status (numerator), as $C_p$ has inverse quadratic relation with flow, any reduction in flow shows non-linear and pronounced increase in $C_p$ as compared to $R$. Therefore, $R$ and $C_p$ are also capable of detecting an outflow stenosis. Thus, combining the flow and pressure data in the functional diagnostic endpoints could improve the ability of these parameters in assessing the patency of AVFs.

**Limitations**
The new functional diagnostic endpoints have not been tested for patient population. Thus, multi-central randomized studies on human subjects are needed to evaluate the potential advantages of the proposed diagnostic parameters for longitudinal assessment of AVF functionality.

**CONCLUSION**

According to KDOQI guidelines, a blood flow ($Q_v$) < 400-500 mL/min and a ratio of venous access pressure to main arterial pressure (VAPR) > 0.55 are associated with the existence of a significant stenosis which needs immediate interventional care. However, an AVF can maintain a relatively high blood flow rate and a normal VAPR despite the presence of a significant stenosis. The $Q_v$ has shown to be a strong predictor of an inflow stenosis, whereas VAPR has shown to be a poor predictor of stenotic lesions in AVFs. These shortcomings have been mainly attributed to the fact that under a developing stenosis both pressure and flow profiles change, and thus, relying on only one of these parameters to detect a significant stenosis could be inadequate. Similar shortcomings also have been reported in detection of coronary and renal stenosis based on diagnostic endpoints that are either based on flow or pressure. In the context of coronary or renal stenosis, it has been shown that the diagnostic endpoints that combine the effects of pressure and flow can better predict the functional severity of a stenosis. This similarity inspired us to bridge between the advances in diagnostic field of coronary and renal stenosis with the diagnosis of stenotic lesions in AVFs. The new functional diagnostic endpoints are based on fundamental fluid dynamics concepts and are primarily presented in two major forms including: (1) resistance index (a ratio of pressure drop by flow); and (2) pressure drop coefficient (the pressure drop normalized by the dynamic pressure). We believe that these endpoints are capable of better distinguishing changes in the hemodynamic variations (pressure and flow) and thus, could be promising diagnostic tools to detect the functional severity of stenosis in AVFs.

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Rajabi-Jaghargh E et al. Functional diagnostic endpoints for arteriovenous fistula. *Artificial Organs* 2014; In press

P- Reviewer: Pan HC, Stolic RV  
S- Editor: Ji FF  
L- Editor: A  
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