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Study on the Correlation between Blood Pressure Variability and Early Arteriovenous Fistula Failure and Recanalization in End-Stage Renal Disease

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Abstract: This study investigates the impact of blood pressure variability (BPV) on early failure and patency outcomes of arteriovenous fistulas (AVFs) in patients with end-stage renal disease (ESRD). Short-term and long-term BPV parameters, including standard deviation of systolic blood pressure (SBP-SD), blood pressure variability coefficient (BCV), and average real variability (ARV), were analyzed in 100 patients who underwent AVF surgery between 2019 and 2023. The results indicate that high BPV significantly increases the risk of early AVF failure (hazard ratio [HR] = 1.48, 95% confidence interval [CI]: 1.23-1.75, $P < 0.01$). Kaplan-Meier analysis revealed a significantly higher rate of patency failure in patients with persistently high BPV (Log-rank $P < 0.01$). The influence of BPV on AVF function is independent of traditional risk factors, suggesting that clinical monitoring and control of BPV can help improve AVF prognosis. Future research is needed to validate its predictive value through larger sample sizes and longer follow-up periods.

1. Background

End-stage renal disease (ESRD) is an irreversible and progressively worsening clinical syndrome characterized by high morbidity and mortality rates, and it significantly increases the risk of cardiovascular diseases[1]. As the glomerular filtration rate (GFR) drops below 15 ml/min/1.73 m^2, ESRD patients often require hemodialysis as the primary treatment modality[2]. Arteriovenous fistula (AVF) is considered the preferred vascular access for hemodialysis in ESRD patients due to its longer survival time, lower complication rates, and cost-effectiveness[3]. According to the Kidney Disease Outcomes Quality Initiative (KDOQI) guidelines, a mature AVF should have a diameter of ≥6 mm and a blood flow rate of ≥600 ml/min. However, despite the critical importance of AVF patency for maintaining dialysis efficacy, early AVF failure remains a common clinical challenge, impacting patients' quality of life and treatment outcomes. The causes of early AVF failure are diverse, including endothelial cell proliferation and inadequate vascular remodeling, which are often influenced by multiple factors such as hemodynamic shear stress, inflammation, and vascular injury. Among these factors, blood pressure variability (BPV) is an increasingly recognized indicator. Studies have shown that BPV not only affects the development and progression of cardiovascular diseases but may also play a pivotal role in early AVF failure[4]. BPV represents an emerging cardiovascular risk factor, and its increase suggests disruption of the normal blood pressure regulatory mechanisms. Existing research indicates that hypotension before and after dialysis is closely associated with early AVF failure, yet the specific mechanisms of short-term and long-term BPV in AVF failure remain unclear. Therefore, an in-depth investigation into the correlation between short-term and long-term BPV and AVF failure is of great significance for improving AVF management and reducing failure rates. Exploring whether effective control of BPV can significantly reduce the early failure rate of AVF could provide clinically actionable interventions.

2. Materials and Methods

2.1 Study Design

This study is divided into three parts, aiming to investigate the correlation between short-term and long-term blood pressure variability (BPV) and early failure as well as recirculation of arteriovenous fistulas (AVFs), and to assess the impact of controlling blood pressure fluctuations on early postoperative failure of AVFs. The study adopts a combined retrospective and prospective design, targeting end-stage renal disease (ESRD) patients who underwent distal arteriovenous fistulization in the Nephrology Department of Jiangxi Provincial People's Hospital between January 2022 and June 2024. This study has been approved by the Ethics Committee of Jiangxi Provincial People's Hospital.

2.2 Study Subjects

Inclusion Criteria:

(1) 100 patients with end-stage renal disease (ESRD) who underwent distal arteriovenous fistula surgery in the Nephrology Department of Jiangxi Provincial People's Hospital between January 2022 and June 2023;

(2) Age ranges from 18 to 75 years inclusive;

(3) Postoperative follow-up for at least 6 weeks.

Exclusion Criteria:

(1) Patients with polycystic kidney disease, malignant tumors, or a history of renal transplantation;

(2) Patients with incomplete medical records or those who were lost to follow-up during the study period.

2.3 Data Collection

The clinical data of all patients were sourced from the electronic medical record system of Jiangxi Provincial People's Hospital. The collected data encompassed general demographic information (age, gender, weight, body mass index), clinical data (dialysis parameters, medications administered, comorbidities), and laboratory test results (such as D-dimer, hemoglobin, serum albumin, phosphorus, parathyroid hormone, etc.). Additionally, detailed records of blood pressure measurements were maintained for all patients both during their hospital stay and after discharge.

2.4 Blood Pressure Measurement and Definition of Blood Pressure Variability

(1) Blood Pressure Measurement:

During Hospitalization: Blood pressure measurements are taken by well-trained nurses on the patient's right or left arm while the patient is in a seated position. Measurements are taken three times at 5-minute intervals, and the average value is recorded. This process is repeated five times daily.

After Discharge: Patients measure their blood pressure at home using the same method as during hospitalization to ensure consistency and reliability in blood pressure measurements.

(2) Blood Pressure Variability Parameters:

Short-term Blood Pressure Variability (BPV): Standard Deviation (SD) of Systolic and Diastolic Blood Pressure: Reflects the degree of blood pressure fluctuation in the short term; Coefficient of Variation (CV): Calculated by dividing the standard deviation by the mean, reflecting the relative variability of blood pressure; Average Real Variability (ARV): Calculates the average of absolute differences between each measurement, reflecting the dynamic fluctuation of blood pressure. Long-term Blood Pressure Variability (BPV): Using the same indicators as short-term BPV (SD, CV, ARV), assesses the patient's long-term blood pressure variability over a 6-week follow-up period through the accumulation of daily blood pressure data.

The specific formula is as follows

1. **Standard Deviation (SD) Formula**:

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(BP_i - BP_{\text{mean}})^2}$$

2. **Coefficient of Variation (CV) Formula**:

$$CV = \frac{SD}{\text{mean}}$$

3. **Average Real Variability (ARV) Formula**:

$$ARV = \frac{1}{n-1}\sum_{k=1}^{n-1}|SBP_{k+1} - SBP_k|$$

2.5 Outcome Measures

Early Failure of Arteriovenous Fistula (AVF): Defined as the inability to use the fistula for dialysis within 6 weeks postoperatively, including a fistula diameter of <6mm, a blood flow rate of <600ml/min, or the occurrence of complications such as thrombosis or fistula occlusion.

Recanalization of Arteriovenous Fistula: Defined as the restoration of patency in the fistula after early failure, achieved through thrombolysis or vascular interventional treatment, with a blood flow rate of ≥600ml/min.

3. Statistical Analysis

All data analyses were conducted using SPSS 23.0 and GraphPad Prism 8.0. For continuous variables, the t-test was employed to compare differences between groups if they followed a normal distribution; otherwise, the Mann-Whitney U test was used. Both univariate and multivariate Cox regression analyses were performed, with adjustments for potential confounding factors such as age, gender, body mass index, and comorbidities. Additionally, Kaplan-Meier survival analysis was utilized to evaluate the impact of long-term blood pressure variability (BPV) on the patency rate of arteriovenous fistulas, and the Log-rank test was applied to compare differences between groups. A two-sided P-value < 0.05 was considered statistically significant for all statistical tests, indicating that differences were statistically meaningful when the P-value was below this threshold.

4. Result

4.1 Patient Characteristics and Clinical Data

In this study, the mean age of the patients was 55.3 ± 12.4 years, with 60 males (60%) and 40 females (40%). There were no significant differences in baseline characteristics (age, gender, body mass index, laboratory indicators) between the two groups (P > 0.05), indicating good comparability. Additionally, the researchers complete data on average blood pressure parameters and blood pressure variability (BPV) were collected. Short-term BPV included standard deviation of systolic blood pressure (BSD), coefficient of variation (BCV), and average real variability (ARV). Significant differences were observed between changes in long-term BPV parameters and ambulatory blood pressure fluctuations during follow-up (see Table 1).

Table 1: Patient Characteristics and Clinical Data

Characteristic	Overall (n=100)	P value
Number of patients	100	-
Age (mean ± SD)	55.3 ± 12.4	-
Male patients	60 (60%)	P > 0.05
Female patients	40 (40%)	P > 0.05
BMI (mean ± SD)	23.5 ± 3.2	P > 0.05
Systolic BP SD (mean ± SD)	9.5 ± 2.1	-
BP Coefficient of Variation (BCV) (mean ± SD)	10.2 ± 1.7	-

4.2 Relationship between Blood Pressure Variability and Early Failure of Arteriovenous Fistula

There are significant differences in blood pressure variability between the successful group and the failure group, particularly in terms of BSD (Beat-to-Beat Systolic Blood Pressure Variability) and BCV (Blood Pressure Coefficient of Variation) of systolic blood pressure, which are closely associated with early failure of arteriovenous fistula (see Table 2 for details).

Table 2: Comparison of Blood Pressure Variability between the Success Group and the Failure Group

Indicator	Success Group (n=65)	Failure Group (n=35)	P value
BSD (mmHg)	9.5 ± 2.1	12.4 ± 3.8	0.002
BCV (%)	10.2 ± 1.7	14.1 ± 2.3	0.001
ARV (mmHg)	8.7 ± 2.5	11.3 ± 3.0	0.004

4.3 Analysis of the Association between Early Failure of Arteriovenous Fistulas and Blood Pressure Variability, and Identification of Predictive Factors

During the 6-week follow-up period, a total of 35 patients experienced early failure of arteriovenous fistulas (AVFs), while 65 patients had normal fistula function. After analyzing the short-term and long-term blood pressure variability (BPV) parameters between the successful and failed groups using t-tests, it was found that the BPV in the early failure group was significantly higher than that in the successful group. Multivariable Cox regression analysis was further employed to verify the independent association between BPV and early AVF failure, controlling for potential confounding factors such as age, gender, BMI, and comorbidities. The results indicated that both short-term BPV parameters, including beat-to-beat standard deviation (BSD), beat-to-beat coefficient of variation (BCV), and average real variability (ARV), were significant predictors of early AVF failure. Notably, BSD of systolic blood pressure demonstrated a significant correlation with the risk of early failure (HR = 1.48, 95% CI: 1.23-1.75, P < 0.01) (see Figure 1).

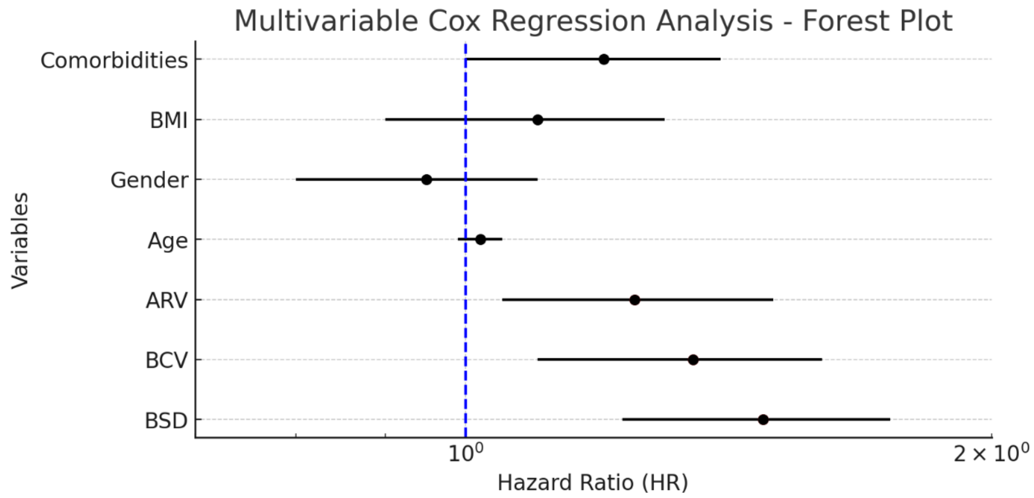

Figure 1: Forest Plot for Multivariable Cox Regression Analysis: Display of Hazard Ratios and Confidence Intervals for Predictors

Forest Plot for Multivariable Cox Regression Analysis: The hazard ratios (HRs) and their 95% confidence intervals for each predictor (e.g., BSD, BCV, ARV, etc.) are represented by black dots and error bars. Significant predictors (with P-values less than 0.05) are highlighted in red. The reference line for HR=1 is displayed as a blue dashed line to aid in observing increases or decreases in risk.

4.4 Relationship between Blood Pressure Variability and Reperfusion

Table 3 demonstrates significant differences in blood pressure variability between the successful and failed reperfusion groups. Both the standard deviation of systolic blood pressure (BSD) and the blood pressure coefficient of variation (BCV) were significantly higher in the failed reperfusion group compared to the successful group (P-values of 0.003 and 0.002, respectively). Specifically, the BSD and BCV in the failed reperfusion group were 12.7 ± 3.7 mmHg and 14.5 ± 2.5%, respectively, whereas in the successful group, they were 9.1 ± 2.4 mmHg and 10.0 ± 1.6%, respectively. These results indicate that failed reperfusion is closely associated with higher blood pressure variability.

Table 3: Comparison of Blood Pressure Variability between the Successful and Failed Recanalization Groups

Indicators	Successful Recanalization Group (n=20)	Failed Recanalization Group (n=15)	Pvalue
BSD (mmHg)	9.1 ±2.4	12.7 ±3.7	0.003
BCV (%)	10.0 ±1.6	14.5 ±2.5	0.002

4.5 Analysis of the Impact of Long-term Blood Pressure Variability on the Outcome of Arteriovenous Fistula Recanalization

Among 35 patients with early failure of arteriovenous fistulas, after thrombolysis and vascular interventional therapy, 20 patients achieved successful recanalization, while 15 patients experienced recanalization failure. Significant differences were observed in blood pressure variability (BPV) parameters between the successful and failed recanalization groups, with long-term BPV demonstrating a strong correlation with recanalization outcomes. Both BSD and BCV were significantly lower in the successful recanalization group compared to the failed group ($P < 0.05$). Kaplan-Meier survival analysis further revealed that patients with higher long-term BPV had a significantly increased risk of recanalization failure (Log-rank $P < 0.01$). A comparison of survival curves highlighted the impact of long-term BPV fluctuations on fistula recanalization (see Figures 2 and 3).

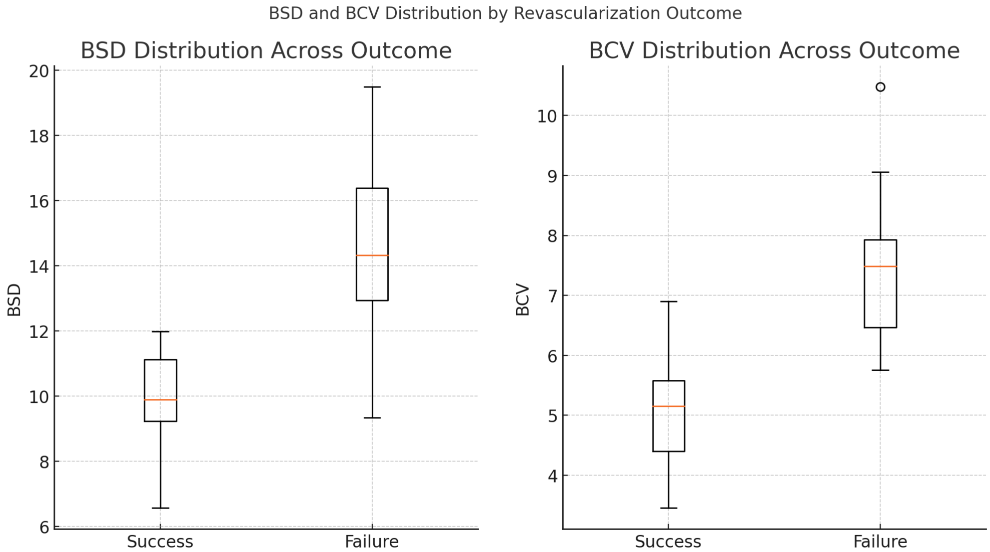

Figure 2: Box Plot Showing the Distribution Differences of BSD and BCV between the Successful and Failed Early Recanalization Groups of Arteriovenous Catheters

This box plot illustrates the distribution differences of BSD (Blood Sugar Standard Deviation) and BCV (Blood Sugar Coefficient of Variation) between the successful and failed groups in early recanalization of arteriovenous catheters. As observed in the figure, the values of BSD and BCV in the successful recanalization group are generally lower than those in the failed group, indicating a significant correlation between lower blood sugar variability and successful recanalization. The distribution of BSD and BCV is categorized based on the outcome of revascularization.

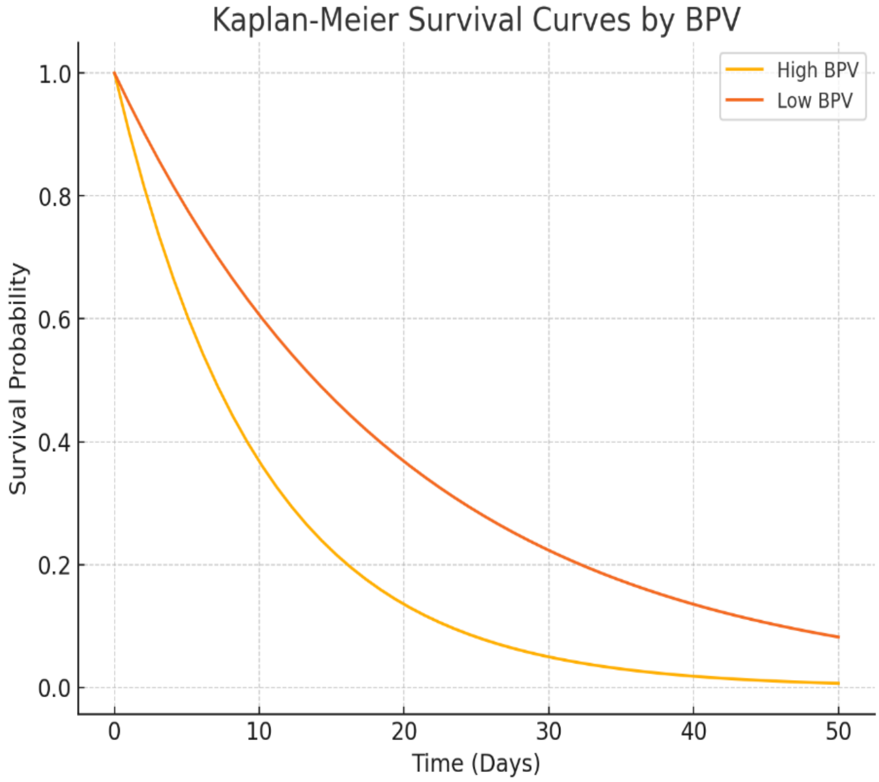

Figure 3: Survival curves for long-term BPV and revascularization outcomes

The Kaplan-Meier survival curve compares the impact of high versus low long-term blood pressure variability (BPV) on the outcome of arteriovenous access patency. The curve indicates that patients with high BPV have a significantly increased likelihood of patency failure (Log-rank P < 0.01), while those with low BPV demonstrate better patency success rates. This suggests that reducing long-term blood pressure fluctuations may have significant clinical value in improving patency outcomes when managing blood glucose levels in patients with venous catheters.

5. Conclusion

This study aims to investigate the pivotal role of blood pressure variability (BPV) in early failure and revascularization treatment of arteriovenous fistulas (AVFs) in patients with end-stage renal disease (ESRD). AVF serves as a crucial access for dialysis treatment in ESRD patients, and the maintenance of its function is closely related to patient prognosis and quality of life. However, AVFs are prone to dysfunction and failure in the early stages of use, posing a persistent challenge in clinical nursing management. Therefore, early identification of risk factors that may affect AVF function is of great significance for optimizing management and improving patient outcomes.

The research results indicate that multiple parameters of blood pressure variability (BPV), including standard deviation of systolic blood pressure (BSD), coefficient of variation of blood pressure (BCV), and average real variability (ARV), play significant predictive roles in the early failure and success rate of recanalization of arteriovenous fistulas (AVFs). These findings offer a new perspective for clinical nursing management, emphasizing the importance of considering BPV, rather than just static blood pressure levels, particularly during the processes of preserving AVF function and recanalization treatment.

Firstly, there are significant differences in both short-term and long-term blood pressure variability (BPV) parameters between the successful and failed groups. Specifically, early failure of arteriovenous fistulas (AVFs) is significantly correlated with standard deviation of systolic blood pressure (BSD), blood pressure coefficient of variation (BCV), and average real variability (ARV). Notably, patients with significantly higher BSD and BCV in short-term BPV are more prone to early failure. This finding suggests that BPV may hold significant value in predicting the risk of AVF dysfunction and early failure. Similar to our research results, other studies have also demonstrated a correlation between BPV and vascular function. Some studies have found that higher levels of BPV increase the risk of cardiovascular events and vascular complications[5]. Particularly in hypertensive patients and those with arteriosclerosis, fluctuations in BPV are believed to exacerbate vascular wall damage [6], leading to hemodynamic instability and decreased vascular function. However, there are also studies that have reported contrasting results, finding no significant association between BPV and some vascular events[7]. These differing results may be attributed to variations in the study populations, methods of BPV measurement, and data collection timelines. Additionally, individual differences in vascular conditions may also influence the impact of BPV on vascular function.

The mechanism through which BPV may affect AVF function is not fully understood. One possible explanation is that blood flow fluctuations caused by high BPV can increase shear stress on the vascular wall, leading to endothelial cell damage, inducing intravascular inflammatory responses and fibrous tissue proliferation, ultimately resulting in AVF dysfunction[8]. Especially in patients with higher short-term BPV, frequent blood pressure fluctuations may have a greater impact on vascular access in the early stages[9], increasing the risk of early failure.

Multivariate Cox regression analysis further validated the independent association between blood pressure variability (BPV) and early arteriovenous fistula (AVF) failure. After controlling for confounding factors such as age, gender, and BMI, standard deviation of systolic blood pressure (BSD), blood pressure coefficient of variation (BCV), and average real variability (ARV) remained significant predictors of early AVF failure. This indicates that the impact of BPV on AVF function is independent, particularly with BSD playing a notably significant role in the risk of early failure, further highlighting the clinical importance of BPV as a predictive factor. Consistent with our findings, other literature has shown that BPV, independently of traditional risk factors, can predict the occurrence of various vascular events and complications. For example, studies have found that even after controlling for other cardiovascular risk factors, BPV still has a significant impact on the occurrence of cardiovascular events[10]， suggesting that BPV may exacerbate vascular damage through independent mechanisms. However, some studies have failed to identify a significant independent effect of BPV, possibly due to differences in sample characteristics, follow-up duration, and statistical models. The underlying mechanisms of BPV as an independent predictor are not yet fully understood. One possible explanation is that fluctuations in BPV may also affect the responsiveness of blood vessels to intrinsic regulatory systems, making them more susceptible to the effects of unstable blood flow[11], leading to early AVF failure.

Furthermore, blood pressure variability (BPV) has also demonstrated a significant impact on the success rate of revascularization therapies. Studies have shown that the standard deviation of systolic blood pressure (BSD) and the coefficient of variation of blood pressure (BCV) are significantly higher in the revascularization failure group compared to the success group, suggesting that patients with greater blood pressure fluctuations are more prone to revascularization failure. Kaplan-Meier survival analysis further corroborates this, indicating a significantly increased risk of revascularization failure in patients with high BPV. This finding highlights the crucial importance of controlling BPV fluctuations in the management of arteriovenous fistula (AVF) revascularization, suggesting that reducing blood pressure fluctuations may be an effective means of improving revascularization outcomes. Similarly, higher BPV increases the risk of vascular complications, particularly during the revascularization process of arteries or veins[12], as fluctuations in BPV can affect the stability and patency of the vascular wall. However, some studies have failed to observe a significant effect of BPV on revascularization outcomes, which may be related to differences in the characteristics of the study populations, methods of BPV monitoring, and revascularization interventions. The mechanism by which BPV affects revascularization success rates may involve frequent blood pressure fluctuations exerting unstable shear stress on the vascular wall[13], leading to damage to vascular endothelial cells and increasing the risk of vascular spasm and thrombosis. Additionally, high BPV may also impair the self-repair capacity of blood vessels[14] , making revascularization more likely to fail.

6. Conclusion

In summary, this study unveils the significant role of blood pressure variability (BPV) in early failure and revascularization therapy of arteriovenous fistulas (AVFs). High levels of BPV are closely associated with poor AVF function and revascularization failure, suggesting that clinical monitoring and control of blood pressure fluctuations should be closely managed to improve AVF outcomes. However, this study also has certain limitations, including a relatively small sample size and a short follow-up period. Future research should expand the sample size and incorporate long-term follow-up to validate the predictive value of BPV in AVF management.

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