Variable Pump Flow–Based Doppler Ultrasound Method: A Novel Approach to the Measurement of Access Flow in Hemodialysis Patients

Chih-Ching Lin,*‖ Chao-Fu Chang,*‖ Hong-Jen Chiou,§‖ Ying-Chou Sun,‡ Shou-Shan Chiang,# Ming-Wei Lin,‖‖ Pui-Ching Lee,‡ and Wu-Chang Yang*‖‖

*Division of Nephrology, †Department of Medicine, ‡Department of Medical Research, and §Division of Ultrasound, Department of Radiology, Taipei Veterans General Hospital, Taipei, Taiwan; †Institute of Clinical Medicine, ‡Faculty of Medicine, National Yang-Ming University, Taipei, Taiwan; and †Division of Nephrology, Department of Medicine, Shin Kong Wu Ho-Su Memorial Hospital

Decreasing vascular access flow (Qa) is an important predictor of future access thrombosis and malfunction for hemodialysis (HD) patients. Among all of the methods for determining Qa, the variable pump flow (VPF) Doppler method measures Qa according to the change in Doppler signal between the arterial and the venous needles under different pump flow. After this technique was combined with spectral analysis of Duplex Doppler imaging, the variable pump flow–based Doppler ultrasound method (VPFDUM) for Qa measurement was developed. This study compared the reproducibility and correlation of Qa measurements for three different methods—VPFDUM, ultrasound dilution method (UDM), and conventional Doppler ultrasound method (CDUM)—in 55 HD patients. The mean value of Qa by VPFDUM (870.8 ± 412.0 ml/min) was close to that by UDM (868.6 ± 417.9 ml/min) but higher than that by CDUM (either of the above values versus 685.1 ± 303.6 ml/min; P < 0.005). The mean values of coefficient of variation were similar by VPFDUM (1.6%) and UDM (1.4%) but lower than that by CDUM (either of the above values versus 6.8%; P < 0.01). The correlation coefficient and intraclass correlation coefficient of the repeated Qa measurements by VPFDUM (0.985 and 0.993; P < 0.001) were also similar to those by UDM (0.992 and 0.995; P < 0.001) but slightly higher than those by CDUM (0.917 and 0.948; P < 0.005). Either the reproducibility of VPFDUM (r = 0.98, P < 0.0001) or the correlation between VPFDUM and UDM (r = 0.99, P < 0.0001) in Qa measurements is good. The unassisted patency of vascular access at 6 mo was significantly poorer in patients with Qa <500 ml/min than those with Qa >500 ml/min (13.6% versus 92.2%; P < 0.0001). In conclusion, VPFDUM is a noninvasive, accurate, and reliable procedure for Qa measurement and prediction of the prognosis of vascular access in HD patients.


The malfunction of vascular access accounts for considerable morbidity and mortality in hemodialysis (HD) patients. It is responsible for 17 to 25% of all hospitalizations among dialysis patients in the United States (1,2). Treatment of these problems requires invasive, expensive, and time-consuming procedures, which are associated with potential risk of complication. Failure of dialysis access can result from either inadequate blood flow on account of stenosis of the venous outflow tract or complete occlusion as a result of thrombosis (3). Decreased access flow is associated with an increased risk for access thrombosis. Access flow (Qa) <400 ml/min in native arteriovenous fistulas (AVF) and <800 ml/min in polytetrafluoroethylene (PTFE) grafts was demonstrated to be predictive of access failure in one ultrasonographic study of 477 AVF and 831 PTFE grafts (4). The methods of measuring Qa include dye dilution (5), constant infusion of technetium-99m (6), Doppler ultrasonography (7), electromagnetic flow meters (8), and magnetic resonance angiography (9). However, some of the above methods are invasive or highly technique dependent, and some require additional laboratory tests. Some of them are impractical and costly or cannot be performed during HD. In the past few years, several noninvasive techniques have been developed for calculating Qa, including ultrasound dilution (10), photo-optical sensor (11), conductivity dialysance (12), thermodilution (13), and ultrafiltration method (14).

Among these methods, the ultrasound dilution method (UDM), developed by Krivitski (10), has been widely accepted as a practical, reliable, and noninvasive method for Qa measurement. Besides, color Doppler ultrasound method additionally provides an anatomic picture of a dialysis access and its venous runoff. It not only is noninvasive but also can be performed serially. However, both of these methods have shortcomings that limit their application in access surveillance. UDM is time-consuming and requires dialysis blood line reversal. Duplex imaging is subject to operator-dependent error and...
is labor-intensive. A novel method (variable flow Doppler method) measures blood flow by using a changing Doppler signal as a function of blood flow in the access during dialysis (15,16). In comparison with the above two methods, the variable flow Doppler procedure does not have the aforementioned drawbacks. However, that technique requires additional equipment that is not easily available. Therefore, we developed a new technique—variable pump flow–based Doppler ultrasound method (VPFDUM)—that combines the advantages of the variable-flow Doppler procedure with additional imaging information of vascular access obtained by spectral analysis of Duplex Doppler study. This study compared Qa measurements by VPFDUM, ultrasound dilution method, and conventional Doppler ultrasound method (CDUM) in HD patients.

**Materials and Methods**

**Patient Selection**

Patients who were included in this study met the following criteria: (1) on maintenance HD for at least 6 mo at Taipei veterans general hospital and (2) present vascular access in use for more than 6 mo, without interventions within the last 3 mo. All patients were dialyzed three times weekly on standard bicarbonate dialysate bath (38 mEq/L HCO3, 3.0 mEq/L Ca++, 2.0 mEq/L K+), using the volumetric-controlled dialysis delivery system under constant dialysate flow at 500 ml/min. Patients were anticoagulated by means of systemic heparin, without change of the individual bolus or maintenance dose throughout the study. After obtaining informed consent from every patient who wanted to participate in this study, we measured Qa according to the following procedures.

**Qa Measurement by UDM**

Qa was measured during HD by UDM using the Transonic HD02 hemodialysis monitor (Transonic Systems, Inc., Ithaca, NY). The technique is widely used and validated extensively in the literature (10). In brief, the technique uses two ultrasound sensors attached to the two HD tubing lines, one to the arterial and another to the venous catheters, approximately 3 to 5 inches distant from the connection of tubing to dialysis needles. Initially, tubing lines are reversed, and ultrafiltration is turned off. The blood pump flow is set at different levels according to the protocol. A measured bolus of saline (10 ml) is injected into the venous catheter, resulting in changes in sound velocity that are measured by the transducers on the catheters. This change is then calculated by the Transonic software, giving the result of Qa (ml/min).

**Qa Measurement by CDUM**

Color Doppler ultrasonography was carried out with commercially available equipment (Model SSA 340A; Toshiba, Tokyo, Japan). The procedure was performed during HD with the patient in a supine position. A 7.5-MHz linear array transducer was placed on the skin, and the angle between the ultrasound beam and the vessel was optimized at 60 degrees. Velocity and Qa were determined by spectral analysis of flow at the site approximately 3 cm upstream from the placement of arterial catheter. The access flow was calculated according to Zierler et al. (17): Access flow (ml/min) = time-averaged maximum velocity (cm/s) × radius² (cm²) × π × 60. All examinations were performed and interpreted under the direction of the same ultrasound expert (H.J.C.).

**Qa Measurement by VPFDUM**

Figure 1 shows the schematic of a dialysis vascular access with flow direction shown by arrows and the probe placement shown by the box. The vascular access flow is represented by Qa, and the pump flow is represented by Qb. As we know, Qa = A × v, where A is the cross-sectional area of the dialysis access and v is the average blood velocity in the vascular access. The access flow detected at transducer site 1 of the vascular access under Qb at 0 is represented by Qa0 (static Qa). The access flow (Qa) may be changed under different Qb. We assumed that the different Qa (Qa(n)) might be correlated with Qa0 (static Qa) and the different pump flow [Qb(n)] as follows:

\[
Qa(n) = Qa0 - k \times Qb(n) \times Qa0 = v(n) \times A
\]

(0)

The abbreviation “(v(n))” represents the velocity detected by the ultrasound probe at transducer site 1 under different pump flow [Qb(n)]. The flow detected by the ultrasound probe at transducer site 1 is represented by Qa1 (under Qb1) or by Qa2 (under Qb2). While the probe is fixed at the same detection angle and placing site during these measurements, the cross-sectional area of dialysis access (represented by A) is the same. We can obtain the following equations:

\[
Qa1 = Qa0 - k \times Qb1 \times Qa0 = v1 \times A \tag{1}
\]

\[
Qa2 = Qa0 - k \times Qb2 \times Qa0 = v2 \times A \tag{2}
\]

Qa0 represents the access flow when Qb is 0 (static access flow), Qb represents the pump flow, Qa1 represents the Qa when Qb is set at Qb1, Qa2 represents the Qa at Qb2, v1 represents the time-averaged velocity (TAV) detected at transducer site 1 under Qb1, v2 represents the TAV detected at transducer site 1 under Qb2, and k is the constant related to the changed Qb and Qa0.

When equation (1) is divided by equation (2), we can obtain k as it is shown in equation (3).

\[
\frac{Qa1}{Qa2} = \frac{Qa0 - k \times Qb1 \times Qa0}{Qa0 - k \times Qb2 \times Qa0} = \frac{v1 \times A}{v2 \times A} \tag{1}
\]

\[
k = \frac{v1 \times Qb1 - v2 \times Qb2}{v1 \times Qb2 - v2 \times Qb1} \tag{2}
\]

If we move the probe at the site downstream from the arterial needle (transducer site 2), then the flow detected by the probe at this site will...
be \([Qa - Qb] \). The flow detected by the ultrasound probe at transducer site 2 will be \([Qa1 - Qb1] \) under \(Qb1\) and \([Qa2 - Qb2] \) under \(Qb2\). While the probe is fixed at the same detection angle and the same placing site during these measurements, the cross-sectional area of dialysis access (represented by \(A')\) will be the same. We can obtain the following equations:

\[
Qa1 - Qb1 = Qa0 - (k \times Qb1 \times Qa0 - Qb1) = v3 \times A' \tag{4}
\]

\[
Qa2 - Qb2 = Qa0 - (k \times Qb2 \times Qa0 - Qb2) = v4 \times A' \tag{5}
\]

\(v3\) represents the TAV detected at transducer site 2 at \(Qb1\), and \(v4\) represents the TAV detected at transducer site 2 at \(Qb2\). If equation (4) is divided by equation (5),

\[
\frac{Qa1 - Qb1}{Qa2 - Qb2} = \frac{Qa0 (1 - k \times Qb1 - Qb1)}{Qa0 (1 - k \times Qb2 - Qb2)} = \frac{v3}{v4} \tag{6}
\]

\(Qa0\) then can be obtained by equation (6) as follows:

\[
Qa0 = \frac{[(v4 \times Qb1) - (v3 \times Qb2)]}{v4 - v3 - k(v4 \times Qb1 - v3 \times Qb2)} \tag{6}
\]

From equation (3), we have obtained that \(k = (v1 - v2)/(v1 \times Qb2 - v2 \times Qb1)\). When we substitute “\((v1 - v2)/(v1 \times Qb2 - v2 \times Qb1)\)” for “\(k\)” in equation (6), we can obtain equation (7) as follows:

\[
Qa0 = \left[\frac{(v4 \times Qb1 - v3 \times Qb2)(v1 \times Qb1 - v2 \times Qb1)}{(v4 - v3) - (v4 \times Qb1 - v3 \times Qb2)(v1 - v2)}\right] \tag{7}
\]

As we assumed that the different \(Qa/Qa(n)\) may be correlated with \(Qa\) and \(Qb\) in the above-mentioned equation (0): \(Qa(n) = Qa0 - k \times Qb(n) \times Qa0\)

\[
Qa(n) = Qa0[1 - k \times Qb(n)] \tag{7}
\]

\(v1 \times Qb2 - v2 \times Qb1)Qb(n)\) [substituting equation (7)]

\[
Qa0 = (v4 \times Qb1 - v3 \times Qb2)\times[(v1 \times Qb2 - v2 \times Qb1) - (v1 - v2) \times Qb(n)]/[v1 \times Qb2 - v2 \times Qb1)] \tag{8}
\]

When we substitute \(Qb1\) for \(Qb\) (n) in equation (8), we can get equation (9):

\[
Qa1 = [(v4 \times Qb1 - v3 \times Qb2) \times [(v1 \times Qb2 - v2 \times Qb1) - (v1 - v2) \times Qb1)]/[v4 \times Qb1 - v3 \times Qb2) \times (v1 - v2)] = (v1 \times Qb1 - v3 \times Qb2) \times (v1 - v2) \tag{9}
\]

When we substitute \(Qb2\) for \(Qb\) (n) in equation (8), we can get equation (10):

\[
Qa2 = [(v4 \times Qb1 - v3 \times Qb2) \times [(v1 \times Qb2 - v2 \times Qb1) - (v1 - v2) \times Qb2)]/[v4 \times Qb1 - v3 \times Qb2) \times (v1 - v2)] = (v1 \times Qb1 - v3 \times Qb2) \times (v1 - v2) \tag{10}
\]

Finally, Y.-C.S. wrote a computerized formula under the structure of the Excel program. After we keyed in the data of \(v1, v2, v3, v4, Qb1,\) and \(Qb2\), we could obtain \(Qa1\) and \(Qa2\) right away.

\section*{Study Procedure for Access Flow Measurement}

\subsection*{I. Protocol for the HD session when initial measurement of access flow is performed}

\begin{itemize}
  \item A. Reversal of arterial and venous lines; for measurement of \(Qa\) by UDM twice according to the following sequence:
    \begin{enumerate}
      \item under \(Qb\) of 250 ml/min
      \item under \(Qb\) of 150 ml/min
    \end{enumerate}
  \item B. Normal position of arterial and venous lines:
    \begin{enumerate}
      \item Measurement of \(Qa\) by CDUM twice according to the following sequence:
        \begin{enumerate}
          \item at transducer site 1 under \(Qb\) of 250 ml/min (Qa1 = v1 × cross-sectional area)
          \item at transducer site 1 under \(Qb\) of 150 ml/min (Qa2 = v2 × cross-sectional area)
        \end{enumerate}
      \item Measurement of \(Qa\) by VPFDUM twice according to the following sequence:
        \begin{enumerate}
          \item using the same \(v1\) obtained by CDUM at transducer site 1 under \(Qb\) of 250 ml/min
          \item using the same \(v2\) obtained by CDUM at transducer site 1 under \(Qb\) of 150 ml/min
          \item obtaining \(v3\) at transducer site 2 under \(Qb\) of 250 ml/min
          \item obtaining \(v4\) at transducer site 2 under \(Qb\) of 150 ml/min
        \end{enumerate}
    \end{enumerate}
\end{itemize}

\subsection*{II. Protocol for measurement of access flow in the two subsequent HD sessions: Measurement of \(Qa\) by VPFDUM once for each dialysis session according to the above-mentioned sequence. Every measurement of \(Qa\) was performed within the first 90 min after the initiation of each HD treatment.}

\section*{Statistical Analyses}

Intermeasurement variation for each patient was expressed as a percentage of the coefficient of variation (CV). Percentage of the CV is defined as the SD in \(Qa\) divided by mean \(Qa\) multiplied by 100 for each patient. Then the mean of the CV of each patient could be calculated. The correlation between repeated measurements or those by different methods was sought using linear regression analysis. The correlation coefficient of this regression line was measured to give an index of measurement reliability. Measurements with \(r^2 > 0.9\) were considered reliable. Intraclass correlation coefficient \((r)\) was used to test (1) the reproducibility of \(Qa\) measurements by one of the three above methods and (2) the agreement of \(Qa\) measurements between different methods. Unassisted survival time of vascular access (which was defined as the time interval from the date of measurement of \(Qa\) to the date of thrombosis) was determined by product-limit life-table distributions and compared using a log-rank test. All tests of significance were two-sided, and differences were considered statistically significant at \(P < 0.05\). SPSS version 11.0 was used for all analyses.

Current guidelines for the combined graphical/statistical interpretation of method-comparison studies include a Bland-Altman plot combined with calculation of the 2 SD limits of the differences (the so-called 95% limits of agreement) between these methods (18). The x-axis shows
the mean of the results of the two methods, whereas the y axis represents the absolute difference between the two methods.

Results

Patient Characteristics

We initially tried to measure Qa in 73 maintenance HD patients by the above three methods. VPFDUM and CDUM can be completed smoothly in all 73 patients. However, UDM failed in 18 patients because blood could not be withdrawn smoothly with reversed lines even under Qb as low as 150 ml/min. Consequently, all three methods could be performed successfully in only 55 patients. Distribution of the clinical characteristics and causes of renal disease in each group is listed in Table 1.

Measurements of Qa by VPFDUM versus UDM or CDUM

The result of Qa measurement by three different methods is shown in Table 2. When we performed repeated measurements of Qa by each one of the three methods, the mean value of Qa by VPFDUM (870.8 ± 412.0 ml/min) was close to that by UDM (868.6 ± 417.9 ml/min) but higher than that by CDUM (either of the above values versus 685.1 ± 303.6 ml/min; P < 0.005). The mean values of the CV were similar by VPFDUM (1.6%) and UDM (1.4%) but lower than that by CDUM (either of the above values versus 6.8%; P < 0.01). The correlation coefficient and intraclass correlation coefficient of the repeated Qa measurements by VPFDUM (0.985 and 0.993; P < 0.001) were also similar to that by UDM (0.992 and 0.995; P < 0.001) but slightly higher than that by CDUM (0.917 and 0.948; P < 0.005). The correlation between repeated measurements of Qa by VPFDUM, with a very good reproducibility (r = 0.98, second measurement of Qa = 1.02 × first measurement of Qa − 9.02; P < 0.0001) is shown in Figure 2. We also measured the Qa in 16 of these patients by VPFDUM during the two subsequent HD sessions. The intraclass correlation coefficient was 0.997 (95% confidence interval from 0.994 to 0.999). This result indicated that the reproducibility and the reliability of this technique were very good.

In comparison with the correlation of Qa measurements between different methods (Table 2), higher regression coefficient (0.93 versus 0.63) and higher intraclass correlation coefficient (0.994 versus 0.856) were noted between VPFDUM and UDM than that between CDUM and UDM. The intraclass correlation coefficient not only between VPFDUM and UDM but also between CDUM and UDM was higher for patients with Qa < 1200 ml/min than that for those with Qa > 1200 ml/min (Table 2). The relationship between measurements of Qa by VPFDUM and UDM is shown in Figure 3, with a good correlation (r = 0.99, measurement of Qa by VPFDUM = 0.933 × measurement of Qa by UDM + 55.2; P < 0.0001).

As illustrated in Figure 4, the Bland-Altman plot reveals the differences in measurements of UDM and VPFDUM versus mean absolute values of these measurements. The mean difference (~3.5 ml/min) did not depend on the absolute value of Qa for most Qa measurements.

Access Survival

We evaluated the effect of Qa measured by VPFDUM on vascular access survival in all of the initially included 73 HD patients in this study. The unassisted patency of vascular access at 6 mo was significantly poorer in patients with Qa < 500 ml/min than those with Qa > 500 ml/min (13.6% [3 of 22] versus 92.2% [47 of 51]; P < 0.0001; Figure 5).

Discussion

Access flow is an important parameter for predicting the prognosis of vascular access. According to Kidney Disease Outcomes Quality Initiative guidelines for vascular access, HD patients with Qa < 600 ml/min or Qa < 1000 ml/min that has decreased by > 25% over 4 mo should be referred for fistulogram (the same threshold for both AVF and graft) (19). Canadian clinical practice guidelines recommend performing angiography when Qa is < 500 ml/min in native arteriovenous fistulas (AVF), which was supported by the study result of Tonelli et al. (20). UDM, invented by Krivitski et al. (10, 21), has been proved to be an accurate and reliable procedure in Qa measurement, but this technique may fail in some patients. The

Table 1. Patient characteristics and causes of renal disease

<table>
<thead>
<tr>
<th></th>
<th>VPFDUM-Completed Group</th>
<th>UDM-Completed Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender (M/F)</td>
<td>40/33</td>
<td>30/25</td>
</tr>
<tr>
<td>Age, yr (mean [range])</td>
<td>62.4 ± 15.3 (30–89)</td>
<td>60.7 ± 13.5 (30–88)</td>
</tr>
<tr>
<td>Access type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVF/AV graft</td>
<td>70/3</td>
<td>53/2</td>
</tr>
<tr>
<td>Cause of renal disease</td>
<td></td>
<td></td>
</tr>
<tr>
<td>diabetes</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>glomerulonephritis</td>
<td>29</td>
<td>26</td>
</tr>
<tr>
<td>hypertension</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>chronic interstitial nephritis</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>miscellaneous</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

aVPFDUM, variable pump flow-based doppler ultrasound method; UDM, ultrasound dilution method; AVF, arteriovenous fistula.
<table>
<thead>
<tr>
<th>Statistical Parameter</th>
<th>Qa by UDM</th>
<th>Qa by CDUM</th>
<th>Qa by VPFDUM</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement of Qa</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>under Qb = 250 ml/min</td>
<td>872.2 ± 432.3</td>
<td>662.2 ± 288.4</td>
<td>868.9 ± 407.4</td>
<td>&lt;0.005(^d); &lt;0.005(^e)</td>
</tr>
<tr>
<td>under Qb = 150 ml/min</td>
<td>977.5 ± 490.6</td>
<td>794.2 ± 376.9</td>
<td>987.0 ± 493.7</td>
<td>&lt;0.005(^d); &lt;0.005(^e)</td>
</tr>
<tr>
<td>Repeated measurements (ml/min; mean ± SD)</td>
<td>868.6 ± 417.9</td>
<td>662.2 ± 303.6</td>
<td>870.8 ± 412.0</td>
<td>&lt;0.005(^d); &lt;0.005(^e)</td>
</tr>
<tr>
<td>extracorporeal blood flow (Qb) during measurement</td>
<td>250 ml/min</td>
<td>250 ml/min</td>
<td>250 ml/min</td>
<td></td>
</tr>
<tr>
<td>mean of coefficient of variation (%)</td>
<td>1.4%</td>
<td>6.8%</td>
<td>1.6%</td>
<td>&lt;0.01(^d); &lt;0.01(^e)</td>
</tr>
<tr>
<td>regression coefficient (^b)</td>
<td>0.93</td>
<td>1.06</td>
<td>1.02</td>
<td>NS</td>
</tr>
<tr>
<td>correlation coefficient ((r))</td>
<td>0.992</td>
<td>0.917</td>
<td>0.985</td>
<td>UDM &lt;0.0001, VPFDUM &lt;0.0001, CDUM &lt;0.005</td>
</tr>
<tr>
<td>intraclass correlation coefficient ((r_i))</td>
<td>0.995 (0.991–0.997)</td>
<td>0.948 (0.904–0.971)</td>
<td>0.993 (0.987–0.996)</td>
<td>UDM &lt;0.001, VPFDUM &lt;0.001, CDUM &lt;0.005</td>
</tr>
<tr>
<td>Comparing with UDM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>regression coefficient (^c)</td>
<td>Omitted</td>
<td>0.63</td>
<td>0.93</td>
<td>Not calculated</td>
</tr>
<tr>
<td>correlation coefficient ((r))</td>
<td>Omitted</td>
<td>0.94</td>
<td>0.99</td>
<td>&lt;0.001(^d); &lt;0.0001(^f)</td>
</tr>
<tr>
<td>intraclass correlation coefficient ((r_i)) for all cases (95% CI)</td>
<td>Omitted</td>
<td>0.856 (0.112–0.953)</td>
<td>0.994 (0.989–0.997)</td>
<td>&lt;0.05(^d); &lt;0.0001(^f)</td>
</tr>
<tr>
<td>for cases with Qa by UDM ≤1200 ml/min (95% CI)</td>
<td>Omitted</td>
<td>0.84 (–0.17–0.96)</td>
<td>0.996 (0.993–0.998)</td>
<td>NS(^d); &lt;0.0005(^f)</td>
</tr>
<tr>
<td>for cases with Qa by UDM &gt;1200 ml/min (95% CI)</td>
<td>Omitted</td>
<td>0.70 (–0.33–0.94)</td>
<td>0.982 (0.918–0.996)</td>
<td>NS(^d); &lt;0.005(^f)</td>
</tr>
</tbody>
</table>

\(^a\)Qa, access flow; Qb, pump flow; CI, confidence interval.
\(^b\)Second measurement of Qa = first measurement of Qa × regression coefficient + intercept.
\(^c\)Measurement of Qa = measurement of Qa by UDM × regression coefficient + intercept.
\(^d\)P value for the comparison between UDM and CDUM.
\(^e\)P value for the comparison between VPFDUM and CDUM.
\(^f\)P value between VPFDUM and UDM.
Following clinical conditions may limit the application of UDM in the measurement of Qa in HD patients: (1) accessory veins may exist between two needles; (2) the length of AVF in some patients may be too short to allow puncture of two needles at the same side of the elbow joint; and (3) some patients have malfunctioning or fragile native AVF, so their blood cannot be withdrawn, even under the setting of Qb < 200 ml/min with reversed lines. This method also carries some disadvantages: (1) reversing lines will increase the workload of nurses in a busy HD center, and (2) infusion of saline may exacerbate the difficulty in attaining ultrafiltration goal in patients with excessive interdialytic body weight gain or preexistent fluid overload. Hence, we would like to develop a new method for measurement of access blood flow without the above-mentioned shortcomings.
Doppler ultrasound method has been used widely to measure Qa; however, our study showed that the accuracy and the reproducibility of CDUM were not as good as that for VPFDUM. This difference may derive from the following reasons. First, the Doppler signal beam angle is an important source of error in flow measurement; accurate angle is necessary for determination of the velocity required for duplex volume flow calculation by CDUM. However, the calculation of Qa will be insensitive to this error by VPFDUM if the Doppler beam angle remains fixed during measurement. Second, a large error in Qa calculations may result from a small change in cross-sectional area of the diameter during study by CDUM. Because VPFDUM does not require calculation of the cross-sectional area, this potential source of error can be avoided by the new technique. We also tried to avoid the influence of turbulence by the following 2 steps: (1) the sampling gate was set at the central part of the vascular lumen to avoid the multidirectional turbulence near the edges of the vessel wall, and (2) the transducer was placed at the site at least 2 cm away from the anastomotic site of the AVF or the stenotic lesion to avoid the turbulence caused by considerable variation of pressure gradient or flow separation zone as a result of different shear stresses.

Although VPFDUM has some advantages over UDM and CDUM and is without their disadvantages, the equations of this study seemed to be more complicated. Originally, we assumed that Qb would not change significantly under different settings of Qb. However, we found that the data of Qa (measured by UDM) would change significantly under different settings of Qb. In 85.5% of these patients (47 of 55), Qa would be increased if Qb were decreased from 150 to 250 ml/min. The mean value of the incremental Qa was 105.3 ml/min (95% confidence interval 77.8 to 132.7 ml/min; P < 0.001), and the increased percentage was 12.1%. Reversely, Qa would be decreased if Qb were increased from 150 to 250 ml/min. Seeing that different Qb will change Qa, we have to take this relationship into consideration. Therefore, we placed the ultrasound probe on transducer site 1 (Figure 1) to detect the possible change in Qa, the degree of which might be influenced by two factors: the static access flow (Qaf0) and the Qb. The final result of good correlation between Qa measurements by VPFDUM and UDM (r² = 0.98, P < 0.0001) also supported that our initial assumption “Qa(n) = Qa – k × Qb(n) × Qa” should be reasonable.

In 1984, van Gemert et al. (22) proposed a two-needle extra-corporeal dialysis circuit model to demonstrate the possible relationship between Qb and other hemodynamic parameters. He concluded that Qb has no instantaneous influence on vascular hemodynamics if Qb is less than Qa. At higher Qa, the BP decreased and the increase in cardiac output was lower than the increase in Qa. However, he did not mention the relationship between Qb and Qa. Further studies should be focused on the relationship between the alteration of some hemodynamic parameters, such as cardiac output, BP, and total peripheral resistance.

In addition to having a good correlation with the currently available methods of flow measurement, a good method should predict access dysfunction reliably and early. For this reason, we evaluated the effect of Qa measurement by VPFDUM on the unassisted patency of vascular access. Because the interventional criteria for AVF was Qa <500 ml/min according to Canadian clinical practice guidelines and Tonelli et al. (20), we also divided our patients into two groups at the value of Qa of 500 ml/min. Patients with lower Qa had significantly poorer patency of vascular access at 6 mo than the higher group did. Therefore, our method can predict effectively the prognosis of vascular access in advance.

In conclusion, our study proved that this novel technique, VPFDUM, not only is as good as ultrasound dilution method but also has several additional advantages, being an accurate, noninvasive, and reliable procedure for measuring the vascular access flow and predicting its prognosis in HD patients.

Acknowledgments
This work was supported by a grant (2004-A042) from Taipei Veterans General Hospital in Taiwan.
This abstract was accepted as a poster presentation at the XLI ERA-EDTA Congress; Lisbon, Portugal; May 15–18, 2004.

References


