Validation of haemodialysis recirculation and access blood flow measured by thermodilution

Daniel Schneditz, Erjun Wang and Nathan W. Levin
Renal Research Institute and Division of Nephrology and Hypertension, Department of Medicine at Beth Israel Medical Center in New York, NY 10128, USA

Abstract

Background. Recirculation (R) and access blood flow (Qac) measurements are considered useful indicators of adequate delivery of haemodialysis. It was the purpose of this study to compare measurements of R and Qac obtained by two different techniques which are based on the same principle of indicator dilution, but which differ because of the characteristics of the injection and detection of the different indicators used.

Methods. Recirculation measured by a thermal dilution technique using temperature sensors (BTM, Fresenius Medical Care) was compared with recirculation measured by a validated saline dilution technique using ultrasonic transducers placed on arterial and venous segments of the extracorporeal circulation (HDM, Transonic Systems, Inc.). Calculated access flows were compared by Bland–Altman analysis. Data are given as mean ± SD.

Results. A total of 104 measurements obtained in 52 treatments (17 patients, 18 accesses) were compared. Recirculation measured with correct placement of blood lines and corrected for the effect of cardiopulmonary recirculation using the 'double recirculation technique' was −0.02 ± 0.14% by the BTM technique and not different from the 0% measured by the HDM technique. Recirculation measured with reversed placement of blood lines and corrected for the effect of cardiopulmonary recirculation was 19.66 ± 10.77% measured by the BTM technique compared with 20.87 ± 11.64% measured by the HDM technique. The difference between techniques was small (−1.21 ± 2.44%) albeit significant. Access flow calculated from BTM recirculation was 1328 ± 627 ml/min compared with 1390 ± 657 ml/min calculated by the HDM technique. There was no bias between techniques.

Conclusion. BTM thermodilution yields results which are consistent with the HDM ultrasound dilution technique with regard to both recirculation and access flow measurement.

Key words: access flow; haemodialysis; recirculation; thermodilution; ultrasound dilution; vascular access

Introduction

The vascular access remains a major cause of complication in haemodialysis patients [1]. Indeed, a growing number of haemodialysis patients suffer from access complications because more patients are dialysed with peripheral polytetrafluoroethylene (PTFE) grafts which have a much reduced life-span when compared with native arterio-venous (AV) fistulae. It is currently under discussion as to whether early signs of access stenosis such as a reduced access flow in PTFE grafts are useful indicators to select for early transcutaneous access revision in order to avoid access thrombosis which requires surgical revision and often causes a loss of the access site [2–5]. A similar consideration applies to the measurement of access recirculation in AV fistulae [6]. There is much interest in techniques measuring recirculation and access flow. Recirculation used to be measured by the urea technique and access blood flow by the ultrasound Doppler technique exclusively [7,8]. These manual techniques are operator dependent, time consuming, and results are often not available at the bedside. Therefore, they were not performed frequently. Recent indicator dilution techniques have considerably simplified the procedure of recirculation and access flow measurements and have the potential to be performed with every treatment [9–14].

One of the first on-line techniques to measure recirculation in haemodialysis patients is based on the measurement of blood temperatures in arterial and venous lines [15]. However, a clinical validation of the Fresenius Blood Temperature Monitor (BTM) has not yet been presented. One of the best studied devices to measure recirculation and access flow is the Transonic Systems Hemodialysis Monitor (HDM). It was the purpose of this study to compare the two techniques.
Recirculation by thermal dilution technique

Materials and methods

Protocol

Measurements were performed during scheduled dialysis treatments in 17 patients who gave informed consent to participate in the study as approved by the Beth Israel Medical Center Institutional Review Board. Patients were studied once a week, and studies in the same access were repeated up to four times. Each study consisted of a series of recirculation measurements done within the first (early) and the last hour (late) of the regular haemodialysis treatment. Data were obtained both with (index n) and without reversed (index x) placement of blood lines. First, the recirculation fraction (R) was measured with the correct position of blood lines using both saline and thermal dilution techniques. Measurements were repeated once. Second, the cardiac output (CO) was obtained by saline dilution. Third, R was measured with the reversed position of blood lines using both saline and thermal dilution techniques. The saline dilution measurement was repeated once, and lines were switched back to the normal position thereafter. The series of measurements was repeated during the last hour of the haemodialysis treatment.

Measurement

Recirculation fractions were measured by saline dilution using the bolus approach and by thermal dilution using the constant infusion approach [11,12,16]. Saline dilution was measured by an ultrasonic technique using the HDM (supplied by Fresenius Medical Care, Bad Homburg, Germany). Thermodilution was measured using the BTM (supplied by Transonic Systems, Inc., Ithaca, NY). Extracorporeal blood flow (Q_b) used in calculations with the BTM technique was read from the arterial blood pump. Cardiac output (CO) was determined from saline dilution and measured by ultrasonic technique as described else- where [17].

Analysis

Recirculation fractions. The recirculation fraction of the thermal indicator for both the correct and reversed position of blood lines (R_BTM,n, R_BTM,x) was obtained directly from the BTM device. The recirculation fraction of saline by the ultrasonic technique was obtained directly from the HDM device with correct placement of blood lines (R_HDM,n). With reversed placement of blood lines, the HDM device presented a value for access flow (Q_ac) but not for the recirculation fraction (R_HDM,x) which was back-calculated from access flow and extracorporeal blood flow as measured by the HDM device according to the following relationship presented elsewhere [11,12]:

\[ R_{HDM,x} = \frac{Q_ac}{Q_{ac,HDM} + Q_{ac}} \]  

(1)

Access component of recirculation fraction. The recirculation fraction measured by the BTM technique always includes a cardiopulmonary component of haemodialysis recirculation [16]. With correct placement of blood lines (index n), the access component of the recirculation fraction measured by the BTM technique is given as the difference between the recirculation fraction determined by the BTM technique (R_BTM,n) and the cardiopulmonary component of the recirculation fraction (R_CPR,n):

\[ R_{BTM,access} = R_{BTM,n} - R_{CPR,n} \]  

(2)

The R_CPR,n is calculated from the extracorporeal blood flow (Q_b,n), access blood flow (Q_ac,n) and cardiopulmonary recirculation (CPR_BTM,n) as described elsewhere [16]:

\[ CPR_{BTM} = \frac{Q_{B,TM,n}}{Q_{ac,BTM,n} - 1 - CPR_{BTM}} \]  

(3)

Access flow is calculated from BTM recirculation with reversed placement of blood lines according to Equation 6. CPR_BTM,n, defined as the ratio of access flow to cardiac output, is determined by the ‘double recirculation technique’ [16]:

\[ CPR_{BTM} = \frac{R_{BTM,n}(1 - R_{BTM,x})}{R_{BTM,n}(1 - R_{BTM,x})} \]  

(4)

The recirculation fractions R_BTM,n and R_BTM,x are measured by the BTM technique using reversed (index x) and correct (index n) placement of blood lines, respectively. Q_b,n and Q_b,x are the extracorporeal blood flows with reversed (index x) and correct (index n) placement of blood lines, respectively.

With the reversed position of blood lines (index x), the access component of the recirculation fraction measured by the BTM technique is derived from a relationship described elsewhere [16]:

\[ R_{BTM,access} = R_{BTM,n} - R_{CPR,n} \]  

(5)

Access blood flow. The access blood flow (Q_ac,BTM) measured by the HDM device was compared with access flow calculated from recirculation fractions measured by the BTM device according to formulae derived previously [16]:

\[ Q_{ac,BTM} = \frac{1 - CPR_{BTM}}{R_{BTM,n}(1 - CPR_{BTM})} Q_{ac,n} \]  

(6)

where CPR_BTM is determined by Equation 4.

Cardiopulmonary recirculation. Cardiopulmonary recirculation determined by the HDM technique (CPR_HDM) was calculated from access flow (Q_ac,HDM) and cardiac output (CO_HDM)

\[ CPR_{HDM} = \frac{Q_{ac,HDM}}{CO_{HDM}} \]  

(7)

and compared with cardiopulmonary recirculation as determined by the BTM technique (CPR_BTM) according to Equation 4.

Cardiac output. Cardiac output by the thermodilution technique was calculated from access flow (Q_ac,BTM) (Equation 6) and cardiopulmonary recirculation (CPR_BTM) (Equation 4) according to the following equation:

\[ CO_{BTM} = \frac{Q_{ac,BTM}}{CPR_{BTM}} \]  

(8)

Data analysis

Data obtained by different techniques were compared by linear regression analysis using identity plots or the
Results

Eighteen accesses (six forearm AV fistulae, five forearm grafts, five upper arm grafts and two thigh grafts) were studied in 17 patients. The calculation of access blood flow depends on whether recirculation also occurs with correct placement of blood lines. Six studies were excluded from further evaluation because of access recirculation of saline determined by the ultrasound technique ($R_{HDM,n} = 27.7\pm17.3\%$). Four accesses were studied four times, nine were studied three times, four were studied twice, and one access was studied once. Both techniques were compared in 104 measurements performed during 52 treatments.

Recirculation fraction

A comparison of recirculation fractions obtained with correct and reversed placement of blood lines is given in Table 1. The mean recirculation fraction obtained with correct placement of blood lines measured by the constant infusion approach was $9.3\pm2.4\%$. The cardiopulmonary component of haemodialysis recirculation as determined

Table 1. Recirculation fraction measured by the BTM ($R_{BTM}$) and HDM technique ($R_{HDM}$) using correct (index n) and reversed (index x) placement of blood lines ($n=104$)

<table>
<thead>
<tr>
<th></th>
<th>$R_{BTM,n}$</th>
<th>$R_{CP,n}$</th>
<th>$R_{ac,n}$</th>
<th>$R_{BTM,x}$</th>
<th>$R_{BTM,ac,x}$</th>
<th>$R_{HDM,x}$</th>
<th>$\Delta R_{x}$</th>
<th>$\Delta R_{ac,x}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>9.35</td>
<td>9.37</td>
<td>-0.02</td>
<td>26.10</td>
<td>19.66</td>
<td>20.87</td>
<td>5.23</td>
<td>-1.21</td>
</tr>
<tr>
<td>SD</td>
<td>2.37</td>
<td>2.38</td>
<td>0.14</td>
<td>10.43</td>
<td>10.77</td>
<td>11.64</td>
<td>2.69</td>
<td>2.44</td>
</tr>
</tbody>
</table>

All values are given as percentages.

$a$Cardiopulmonary component of haemodialysis recirculation as determined from Equation 3.

$b$Access component of haemodialysis recirculation as determined from Equation 2.

$c$Access component of haemodialysis recirculation as determined from Equation 5.

$d$Difference of recirculation fractions with reversed placement of blood lines calculated as $R_{BTM,x} - R_{HDM,x}$.

$e$Difference of recirculation fractions with reversed placement of blood lines calculated as $R_{BTM,ac,x} - R_{HDM,x}$, where $R_{BTM,ac,x}$ is the access component of haemodialysis recirculation as determined from Equation 5.
by the thermodilution technique was 9.4 ± 2.4%. Therefore, the access component of haemodialysis recirculation was not different from zero measured by the saline bolus technique (P = not significant, NS) (Figure 1).

The mean recirculation fraction obtained with reversed placement of blood lines and measured by the constant infusion approach \( R_{BTM,ac} = 26.1 ± 10.4\% \) was significantly higher when compared with values obtained by the saline bolus technique \( R_{HDM,ac} = 20.9 ± 11.6\% \). When corrected for the cardiopulmonary component of recirculation according to Equation 5, a small albeit significant difference between techniques \((-1.21 ± 2.44\%, \ P < 0.01\) persisted (Figure 2). A strong linear relationship between techniques was obtained \( R_{BTM,ac,rel} = 0.74 + 0.91R_{HDM,ac}\) with a range of 2–65% (Figure 5).

Cardiopulmonary recirculation and cardiac output

Mean cardiopulmonary recirculation was 23 ± 10% by thermodilution and 22 ± 11% by the saline dilution technique, with a range of 2–65% (Figure 5). Cardiopulmonary recirculation determined by both techniques showed a strong linear relationship \( CPR_{BTM} = 7.3 + 0.073CPR_{HDM}\) \( r^2 = 0.66 \) (Figure 5). Cardiac output measured by thermodilution and saline dilution was 5.6 ± 1.4 and 6.7 ± 1.6 l/min, respectively (Figure 6).

Repeatability

The repeatability of the different techniques was assessed by calculating and analysing the absolute \( AX = X_2 - X_1\) and relative difference \( \Delta X_{rel} = X_2/X_1 - 1\) of subsequent measurements (Table 3). Even though there was a trend for recirculation fractions to decrease, mean absolute and mean relative differences of subsequent recirculation measurements were not different from zero by both thermodilution and saline dilution techniques. The relative error for the recirculation fraction measured by thermodilution with correct placement of blood lines was better than ±20%. With a mean recirculation fraction of ~10% (Table 1), this translates into an absolute error of ±2%. The recirculation fraction measured by saline dilution with correct placement of blood lines was not available. The relative error for the recirculation fraction measured with reversed placement of blood lines was less than ±12% by both thermodilution and saline dilution techniques. With a mean recirculation fraction of ~25% (Table 1), this translates into an absolute error of ±3%. Thus, the absolute error increased and

![Access blood flows (mean ± SD) measured in 18 PTFE grafts by the thermodilution and saline dilution technique. Mean and standard deviation of all measurements obtained with each access.](image)
Discussion

This study presents a comparison of two technical approaches to measure recirculation and access blood flow in haemodialysis patients. Both techniques are based on indicator dilution measurements performed during haemodialysis using correct and reversed placement of blood lines. However, both techniques have characteristic features as far as the timing of procedures and the type of indicators used are concerned. The ultrasonic dilution used in the HDM is based on bolus injection of saline and on rapid detection of indicator transients in venous and arterial blood lines as described elsewhere [11,12]. The thermodilution used in the BTM is based on changing dialysate temperatures, which will change the venous blood temperature returning to the patient. However, blood temperature changes do not occur instantaneously and the technique rather follows the constant infusion principle (Fick principle) which will include effects caused by recirculation of indicator through the cardiopulmonary circulation. The theoretical difference between bolus and constant infusion approaches has been analysed elsewhere [16]. It was shown that effects of the local, access and of the central, cardiopulmonary component of recirculation measured by the constant infusion approach can be separated using the ‘double recirculation technique’ when recirculation fractions are measured both with correct and reversed positions of blood lines.

Separation of the central, cardiopulmonary component of recirculation from the recirculation fraction measured by the BTM technique showed that the access component of BTM recirculation was indeed zero (−0.02%) in those patients in whom access recirculation was absent, and that the standard deviation of the measurement was very small (±0.14%).

Following the approach introduced by Krivitski, access blood flow was calculated from a recirculation measurement obtained with reversed position of blood lines. The local access component of BTM recirculation determined from the double recirculation technique

the relative error decreased with increasing recirculation. The relative error in the measurement of access flow was better than 19 and 16% by thermodilution and saline dilution techniques, respectively. With a mean access flow of 1300 ml/min, this translates into an absolute error of ±250 ml/min by thermodilution compared with approximately ±170 ml/min by saline dilution. The relative error in the measurement of cardiac output was ±18 and ±15% by thermodilution and saline dilution techniques, respectively.

Fig. 5. Cardiopulmonary recirculation measured by the saline dilution technique ($\text{CPR}_{\text{HDM}}$) according to Equation 7, and the thermal dilution technique ($\text{CPR}_{\text{BTM}}$) according to Equation 4.
Recirculation by thermal dilution technique

Fig. 7. Error in access flow measurement. The error of calculated access blood flow relative to extracorporeal blood flow ($dQ_{ac}/Q_b$) plotted against the recirculation fraction measured with reversed placement of blood lines ($R_x$) for saline dilution (dotted line) and thermodilution techniques (full and broken lines) (Equations 11 and 12). Representative values for $R_n$ (10%), $dR_n$ (±20%) and $dR_x$ = (±10%) are taken from experimental data (Table 3). The error $dQ_{ac}/Q_b$ decreases with increasing recirculation fraction and reaches 10% of the extracorporeal blood flow at $R_x = 100%$. If the error goes in the same direction for both $dR_n$ and $dR_x$, the error of the thermodilution technique (broken line) is comparable with the error of the saline dilution technique (dotted line) for $R_x > 20%$.

Fig. 6. Comparison of cardiac output (CO) measured by the thermal dilution and saline dilution technique. (a) Comparison of repeated measurements by the thermodilution technique ($CO_{BTM}$). (b) Comparison of repeated measurements by the saline dilution technique ($CO_{HDM}$). (c) Comparison of measurements by the thermodilution ($CO_{BTM}$) and saline dilution technique ($CO_{HDM}$).

was only 1.2% (but significantly) smaller than the value obtained by the HDM technique. This could be related to a loss of thermal indicator in central parts of the circulation.

While still close to the line of identity, two measurements in the same access with recirculation fractions of ~80% stand out in the whole group of measurements which have a range between 10 and 50%, respectively (Figure 2). In this access, reversal of blood lines produced increased recirculation fractions which were consistent with an access flow of <100 ml/min (Figure 3). However, no access recirculation was present with correct placement of blood lines at an extracorporeal blood flow of 300 ml/min. What had happened in this access? With intra-access strictures between the arterial and venous needle puncture sites, blood flow takes a functional bypass through the extracorporeal circulation with correct placement of blood lines [19,20]. $Q_{ac,n}$ is larger than $Q_{b,n}$ and there is no recirculation. However, when blood lines are reversed, extracorporeal blood flow is forced through the intra-access stricture, and access blood flow adjusts to the resistance given by the stricture: $Q_{ac,x}$ is then smaller than $Q_{b,x}$. Thus, the absence of access recirculation with correct placement of blood lines is not an indicator for absence of access problems. However, a measurement of recirculation with reversed placement of blood lines identifies the access at risk, and a recirculation fraction of >50% with reversed placement of blood lines is an indicator of access recirculation and/or intra-access stricture.

The comparison of access blood flows showed no bias between techniques for the observed range of blood flows (400–3000 ml/min) (Figure 4). In the mean, access flow was underestimated by the BTM technique by 3.8%. The standard deviation of ±16.4% for the relative difference between techniques was consistent with a reported coefficient of variation in the range of 10% for both techniques.

The variability of the thermodilution technique is comparable with that of the saline dilution technique as far as the measurement of recirculation fractions is concerned (12% vs 10%, Table 3), and the variability in the measurement of access blood flow by the thermodilution technique is only marginally larger than that by the saline dilution technique (19% vs 16%, Table 3).
Even though the thermodilution technique relies on two recirculation measurements, it can be shown that if the errors \( \Delta R_e \) have the same sign, the error in the thermodilution technique will be almost identical to the error measured by the saline dilution technique (Appendix, Figure 7). It appears from the experimental results that parallel errors (over- or underestimation in both \( R_e \) and \( R_a \)) are more likely to occur in experimental situations than antiparallel errors (over- or underestimation of either \( R_e \) or \( R_a \)).

Comparison of cardiopulmonary recirculation determined by the HDM and BTM techniques gave a strong linear correlation. The highest value for CPR was observed in a small patient with a forearm fistula where ~50% of the cardiac output—as identified by both techniques—was consumed by access flow. Even though the patient did not show clinical symptoms, such high fractions of CPR must be considered a major haemodynamic perturbation. The possible consequences remain an under-recognized phenomenon in haemodialysis patients.

In summary, BTM thermodilution yields results which are consistent with the HDM ultrasound dilution technique with regard to both recirculation and access flow measurement.

**Appendix**

The calculation of access flow by the double recirculation technique is based on two measurements of recirculation fraction \( R_e \), one with correct (index \( b \)) and one with reversed (index \( x \)) placement of blood lines. If the blood flows are the same both with correct and with reversed placement of blood lines \( Q_{b,n} = Q_{x,n} \), Equation 6 simplifies to

\[
Q_{x,\text{HDM}} = \left( 1 - R_e \right) \frac{1 - R_a}{R_a - R_e} Q_o
\]

Assume an error \( dR_a \) and \( dR_e \) in the measurement of recirculation fractions, then the error \( dQ_{x,\text{BTM}} \) relative to the extracorporeal blood flow \( Q_o \) is given by

\[
dQ_{x,\text{BTM}} = \left[ \left( R_a - 1 \right) dR_a + \left( R_e - 1 \right) dR_e \right] Q_o / \left( R_a - R_e \right)^2
\]

Because of the negative sign in Equation 11, the errors tend to cancel out if they are both positive or both negative. The errors tend to add up if one of them is positive and the other one is negative.

The error to be expected by the saline dilution technique is given by

\[
dQ_{x,\text{HDM}} = 1 / R_e \cdot dR_e
\]

A comparison of errors to be expected by thermodilution and saline dilution techniques for the whole range of recirculation fractions and assuming a reproducibility of \( \pm 10\% \) and \( \pm 20\% \) for \( R_e \) and \( R_a \), according to the results of this study (Table 3), is given in Figure 7. The error tends to decrease with increasing recirculation fraction measured with reversed placement of blood lines \( R_e \). If both errors are positive or negative, the errors expected for the thermodilution technique and the saline dilution technique are comparable for \( R_e > 20\% \).

**References**


---

**Table 3. Relative and absolute differences between repeated recirculation \( R_e \), access flow \( Q_{ac} \) and cardiac output \( CO \) measurements**

<table>
<thead>
<tr>
<th>( \Delta X_{rel} )</th>
<th>SD</th>
<th>( X_{rel} )</th>
<th>SD</th>
<th>Count</th>
<th>( P^{*} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{BTM}(2), R_{BTM}(1)^x )</td>
<td>-0.060</td>
<td>0.20</td>
<td>-0.80%</td>
<td>1.83%</td>
<td>51</td>
</tr>
<tr>
<td>( R_{BTM}(3), R_{BTM}(3)^x )</td>
<td>-0.039</td>
<td>0.20</td>
<td>0.40%</td>
<td>1.84%</td>
<td>52</td>
</tr>
<tr>
<td>( R_{HDM}(late), R_{HDM}(early) )</td>
<td>-0.002</td>
<td>0.12</td>
<td>-0.29%</td>
<td>3.26%</td>
<td>52</td>
</tr>
<tr>
<td>( Q_{ac,BTM}(late), Q_{ac,BTM}(early) )</td>
<td>-0.018</td>
<td>0.10</td>
<td>-0.38%</td>
<td>2.96%</td>
<td>52</td>
</tr>
<tr>
<td>( Q_{ac,HDM}(2), Q_{ac,HDM}(1)^x )</td>
<td>0.005</td>
<td>0.19</td>
<td>26 ml/min</td>
<td>298 ml/min</td>
<td>52</td>
</tr>
<tr>
<td>( Q_{ac,HDM}(4), Q_{ac,HDM}(3)^x )</td>
<td>0.017</td>
<td>0.12</td>
<td>19 ml/min</td>
<td>191 ml/min</td>
<td>52</td>
</tr>
<tr>
<td>( Q_{ac,HDM}(4), Q_{ac,HDM}(1)^x )</td>
<td>0.026</td>
<td>0.16</td>
<td>27 ml/min</td>
<td>212 ml/min</td>
<td>52</td>
</tr>
<tr>
<td>( CO_{BTM}(late), CO_{BTM}(early) )</td>
<td>0.030</td>
<td>0.18</td>
<td>98 ml/min</td>
<td>1126 ml/min</td>
<td>51</td>
</tr>
<tr>
<td>( CO_{HDM}(late), CO_{HDM}(early) )</td>
<td>-0.068</td>
<td>0.15</td>
<td>-543 ml/min</td>
<td>1175 ml/min</td>
<td>51</td>
</tr>
</tbody>
</table>

\*Mean relative difference of repeated measurements (\( \Delta X_{rel} = X_2/X_1 - 1 \)).
\*Mean absolute difference of repeated measurements (\( \Delta X = X_2 - X_1 \)).
\*Non parametric one-sample sign test for a mean difference of \( H_0 = 0 \).

\*Difference between first and second measurement early in dialysis.
\*Difference between third and fourth measurement late in dialysis.
\*Difference between first measurement early and last measurement late in dialysis.
Recirculation by thermal dilution technique


Received for publication: 26.6.98
Accepted in revised form: 6.10.98