Technical Note

Within-session and between-session variability of haemodialysis shunt flow measurements

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Abstract

Background. Knowledge of the variability of a measurement method is essential for its clinical application. We investigated the variability of shunt flow measurements, since this is a relatively neglected area in the literature. In particular, no direct comparison of between-session and within-session variability was available until now.

Methods. During two consecutive dialysis sessions, shunt flow was measured three times with the ultrasound dilution method in 24 chronic haemodialysis patients with various types of shunts. Needle orientation and blood pressure at the time of flow measurement were recorded. In these patients, shunt flow was also measured three times by duplex ultrasound before the first dialysis session.

Results. The within-session variation coefficient (VC) of shunt flow measured with ultrasound dilution was 7.7%, whereas the between-session VC was 14.2% (n.s.). The within-session VC of Doppler shunt flow was 11.6% which was not significantly different from the corresponding figure of ultrasound dilution. Analysis of subgroups showed that changes in needle orientation caused large differences between sessions in radiocephalic fistulas but not in brachiocephalic fistulas: in the radiocephalic fistulas with the same needle orientation, VC was 6.7%, but with different needle orientation it was 23.5% (\( P = 0.02 \)); the corresponding figures for brachiocephalic fistulas were 14.6% (same direction) and 11.4% (different direction, n.s.).

Conclusion. Reproducibility of shunt flow measurements between dialysis sessions in radiocephalic fistulas is critically dependent on similar needle orientation. With similar needle position and correction for blood pressure differences, flow changes of more than 20–25% are likely to reflect true flow changes. The variability of duplex flow measurements is at least as large as that of the ultrasound dilution method.

Keywords: duplex ultrasound; haemodialysis; shunt flow; ultrasound dilution; variability

Introduction

In arteriovenous fistulas as well as in grafts, the standard for shunt surveillance is periodic measurement of blood flow through the shunt [1,2]. It has been shown that a low blood flow through the shunt is predictive of thrombotic occlusion, but a decreasing trend in shunt flow even more so [3]. If the cause of such a decrease, usually a stenosis in the shunt or its afferent or efferent vessels, is located and treated, the incidence of thrombotic occlusions can be decreased substantially [4]. However, flow measurements have their limitations: the reliability of individual measurements is only mediocre, caused by inaccuracies of the measurement and the dependence of shunt flow on blood pressure. If one is not aware of the magnitude of the errors involved, unnecessary invasive diagnostic action may be taken.

All flow measurements, with the possible exception of timed collection of actual transported fluid volume, are relatively inaccurate, i.e. variation coefficients are usually in the order of 10%, even if close-fitting electromagnetic or ultrasonic flow probes are used [5]. Therefore, using flow measurements as an early warning system of shunt dysfunction has the risk of many false positive or false negative findings depending on the limits used to define a significant change. The most often used method to monitor shunt flow is ultrasound dilution, in which physiological salt solution is used as an indicator which changes the velocity of ultrasound in blood.

The inventor of ultrasound dilution shunt flow monitoring initially reported a mean error of 3–6%
in a flow range of 150–350 ml/min during in vitro testing [6]. In vivo testing resulted in an estimate of the variation coefficient of 5% [7], 7% [8,9] or 13% [10] if results are compared, which are obtained closely after one another during the same dialysis session. For clinical use, however, one is more interested in the variability of flow measurements between dialysis sessions than within sessions. In comparisons between sessions, differences in needle placement and differences in haemodynamics will cause larger variability. These values are more difficult to find in the literature. The purpose of the present study was to compare within-session variability of ultrasound dilution flow measurements to between-session variability. We also compared these shunt flow values with duplex flow measurements on the same day.

Methods

Study design and demographics

The measurements were performed from October through December 2003 in an outpatient dialysis centre (Dialyse Centrum Groningen, ultrasound dilution) and in the Groningen University Medical Centre (surgical vascular function lab, duplex flow). Informed consent was obtained from all patients. Excluded were those patients who were on single-needle dialysis (ultrasound dilution measurements not possible) and patients who were too frail to visit the vascular function lab. All other patients in whom the shunt flow was examined in the given time frame were included. Two patients who had a shunt stenosis were included, since a second measurement was possible before intervention took place and flow had not changed appreciably during the 2-day interval. By including these patients, the studied flow range could be extended. A total of 24 patients participated, eight women and 16 men, with an age range of 15–81 years (mean age 59 years). Only three of these patients had a polytetra-fluoroethylene (PTFE) graft, 10 had a radiocephalic and 11 had a brachiocephalic fistula.

Flow measurements

In 48 dialysis sessions (two sequential dialysis sessions in each patient with 1 day in between), flow was measured three times in rapid succession during the first hour of dialysis. Shortly before dialysis and only on the day of the first dialysis session, shunt flow was measured three times with duplex ultrasound. All measurements using ultrasound dilution were done by the same technician, who was not aware of the duplex flow results. Another technician performed all duplex flow measurements. Just before flow measurements, blood pressure was measured using a Dinamap Compact monitor (Johnson and Johnson Critikon, Tampa, Florida, USA).

The ultrasound dilution flow measurements were performed with a Transonic HD01plus Haemodialysis Monitor (Transonic Systems Inc., Ithaca, NY, USA). For Doppler flow measurements, a pulsed wave Doppler system was used (Sonoline Antares, Siemens Nederland b.v., The Hague, Netherlands) with a multifrequency probe (VFX 13-5) set at a frequency of 10 MHz. Flow velocities were measured over the diameter of the vessel and integrated to obtain volume flow. The measurement site was always located between the arterial and venous puncture locations. Care was taken to select a (nearly) circular cross-section for measurement and to exert only little pressure to avoid flattening of the vessel.

Table 1. Mean, median and range of measured shunt flows, plus flows corrected for differences in mean arterial pressure and relative difference between first and second session

<table>
<thead>
<tr>
<th></th>
<th>Session 1</th>
<th>Session 2</th>
<th>Relative difference between the two sessions (%)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Median</td>
<td>Range</td>
</tr>
<tr>
<td></td>
<td>(ml/min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duplex flow</td>
<td>857 (480)</td>
<td>790</td>
<td>161–2126</td>
</tr>
<tr>
<td>Duplex flow at MAP 100</td>
<td>827 (533)</td>
<td>664</td>
<td>145–2572</td>
</tr>
<tr>
<td>mmHg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dilution flow</td>
<td>1138 (619)</td>
<td>1064</td>
<td>153–2490</td>
</tr>
<tr>
<td>Dilution flow at MAP 100</td>
<td>1164 (760)</td>
<td>930</td>
<td>128–3220</td>
</tr>
<tr>
<td>mmHg</td>
<td></td>
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</table>

Statistical analysis

Two ways to express variability were used. Variability of two measurements was expressed as the relative difference of the highest minus the lowest value:

\[
2 \times \frac{\text{value}_1 - \text{value}_2}{\text{value}_1 + \text{value}_2}
\]

In comparisons which involved variability of more than two measurements, the variation coefficient was calculated: SD/mean. Pooled variation coefficients were calculated as the root mean square of the variation coefficients.

Comparisons of means were done using the \( t \)-test, for paired samples if appropriate. Comparisons of variation coefficients were done with an \( F \)-test. Differences with \( P < 0.05 \) were considered statistically significant. The statistical analysis was done with SPSS 10.0 software.

Results

In the first dialysis session, shunt flow measured with ultrasound dilution ranged from 153–2490 ml/min (mean 1138 ml/min). Repeated flow measurements during the next dialysis session resulted in a range of 197–2837 ml/min (mean 1242 ml/min; n.s.). A comparison of the means of three flow measurements in two sequential dialyses in 24 patients showed a mean difference of 16.4% (SD 11.9%) between average shunt flows in the two sessions (see Table 1, in which medians
and ranges are also given). In 11 patients, shunt flow was higher in the first session, in 13 patients it was highest in the second session. To compare the between-session variability with the within-session variability, the pooled between-session variation coefficient was also calculated, using the same data, which had a value of 14.2%. This was not significantly different from the pooled within-session variation coefficient of 7.7% ($P = 0.25$). We then analysed whether differences in shunt type, needle orientation or blood pressure were associated with variability in blood flow measurements.

Initial body weight did not appear to contribute significantly to the variability. The mean difference between sessions was only 0.7 kg (SD 0.5 kg). In 14 patients, the change in shunt flow was opposite to the change in initial body weight, in nine patients it went in the same direction, and in one patient, the initial weight was the same in both sessions (n.s.). Differences in blood pressure or in needle orientation could have played a role in causing the increase in variability between dialysis sessions as compared to within sessions. When we divided flows by the existing mean arterial blood pressure (MAP) at the moment of measurement, in order to estimate the contribution of blood pressure, this did not diminish the differences between the two sessions (pooled VC = 15.5%, as compared to 14.2% without blood pressure correction).

Radiocephalic and brachiocephalic fistulas did not differ in this respect. In Table 1, this shunt flow corrected for blood pressure differences, a measure of hydraulic conductance, is given as flow at a MAP of 100 mmHg.

In an attempt to differentiate between the effects of needle orientation and blood pressure, we first compared actual flows measured with ultrasound dilution in the 10 cases in which the dialysis needles had been placed in the same direction during the two dialyses with the 11 cases in which they were directed differently (in the remaining three patients, the needle orientation was unknown in one of the sessions). This resulted in a mean difference of 12.7% (SD 10.4%) with similar needle orientation, whereas it was 21.3% (SD 12.7%) with different needle orientation ($P = 0.08$, n.s.). When flows were corrected for mean blood pressure, the differences associated with needle orientation increased: mean difference 10.1% (SD 11.8%) with similar needle orientation and 26.0% (SD 13.0%) with different needle orientations in the two sessions ($P < 0.01$) (Figure 1). A comparison of variation coefficients in the various situations yielded essentially the same results. From the results in the 10 patients with similar needle placement in the two sessions, corrected for blood pressure, the 95% confidence interval of the difference between two dialysis sessions with, in fact, the same flow was 1.8–18.5%. Values outside this range could be considered a significant flow change.

We also checked whether the sensitivity for needle orientation differed in the two kinds of fistulas. This appeared to be the case, even though the numbers were small: only the radiocephalic fistulas showed smaller differences with similar needle orientation (mean 7.3% vs. 27.6%, $n = 8$, $P = 0.05$), whereas brachiocephalic shunts did not show this phenomenon (18.0% difference with similar needle orientation and 14.8% with different needle orientation, $n = 10$, n.s.). Variation coefficients for radiocephalic shunts with the same and different needle orientation were 6.7% and 23.5% ($P = 0.02$), respectively. For brachiocephalic shunts, these values were 14.6 and 11.4% (n.s.). In Tables 2 and 3, detailed values for the variation coefficients in the various situations are given.

Flow rates measured by duplex ultrasound before dialysis had a range of 161–2126 ml/min (mean 857 ml/min). These values represent the mean of three separate measurements. Since shunt flow by duplex ultrasound was measured in one session only, we can only present here data on the within-session variability.

Figure 1. Box-and-whisker plots of the differences between shunt flow measurements (corrected for mean arterial blood pressure) in two sequential dialysis sessions when the needles were either pointing similarly or differently in the two sessions. The mean difference in the first case was 10.1%, in the second case it was 26.0% ($P < 0.01$).

### Table 2. Pooled between-session variation coefficients for flow measurements in fistulas

<table>
<thead>
<tr>
<th></th>
<th>Radiocephalic fistula</th>
<th>Brachiocephalic fistula</th>
<th>Pooled VC (row)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same direction</td>
<td>6.7% ($n = 5$)*</td>
<td>14.6% ($n = 5$)</td>
<td>11.3% ($n = 10$)</td>
</tr>
<tr>
<td>Different direction</td>
<td>23.5% ($n = 3$)*</td>
<td>11.4% ($n = 6$)</td>
<td>16.4% ($n = 9$)</td>
</tr>
<tr>
<td>Pooled VC (column)</td>
<td>14.2% ($n = 10$)</td>
<td>12.9% ($n = 11$)</td>
<td>13.6% ($n = 21$)</td>
</tr>
</tbody>
</table>

* $P < 0.05$. 

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of this method. The pooled within-session variation coefficient of duplex flow measurements was 11.6%, which was not significantly different from the within-session variation coefficient of ultrasound dilution flow measurements. Both flow measurement methods showed a reasonable correlation \( r = 0.690, P < 0.01 \); Figure 2), but in individual cases, there were large differences (Figure 3). Correction for mean blood pressure resulted in only a very slight improvement of correlation \( r = 0.696, P < 0.01 \). Flow measured by Doppler was significantly lower than by ultrasound dilution \( P < 0.01 \), and data fitted the regression equation \( \text{Flow}_{\text{doppler}} = 0.704 \times \text{Flow}_{\text{dilution}} \).

**Discussion**

This study shows the within-session variation coefficient of shunt flow measurement by ultrasound dilution to be 7.7%. Correction for mean blood pressure resulted in only a very slight improvement of correlation \( r = 0.696, P < 0.01 \). Flow measured by Doppler was significantly lower than by ultrasound dilution \( P < 0.01 \), and data fitted the regression equation \( \text{Flow}_{\text{doppler}} = 0.704 \times \text{Flow}_{\text{dilution}} \).

Variability of haemodialysis shunt flow measurements

**Table 3.** Pooled within-session variation coefficients for flow measurements in fistulas

<table>
<thead>
<tr>
<th></th>
<th>Radiocephalic fistula</th>
<th>Brachiocephalic fistula</th>
<th>Pooled VC (row)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same direction</td>
<td>7.1% ((n = 10))</td>
<td>9.5% ((n = 10))</td>
<td>8.4% ((n = 20))</td>
</tr>
<tr>
<td>Different direction</td>
<td>7.1% ((n = 6))</td>
<td>7.6% ((n = 12))</td>
<td>7.4% ((n = 18))</td>
</tr>
<tr>
<td>Pooled VC (column)</td>
<td>7.0% ((n = 20))</td>
<td>8.5% ((n = 22))</td>
<td>7.8% ((n = 42))</td>
</tr>
</tbody>
</table>

**Fig. 2.** Correlation in 24 patients between shunt flow measured on the same day by two methods: just before dialysis by duplex method (horizontal axis) and during dialysis by ultrasound dilution (vertical axis): \( r = 0.690, P < 0.01 \).

**Fig. 3.** Bland Altman plot of shunt flow measurements by ultrasound dilution vs duplex ultrasound in 24 patients. On the vertical axis, the difference between the two flow measurements is shown (dilution – Doppler), whereas the horizontal axis represent the average of the two measurements. The dispersion increases with a increasing flow.
The very small effects of correction for actual blood pressure values that we found may at first appear to be in contrast with some other reports [11,13] and with theoretical expectations. However, one should realize that, although our patients had not been selected for stable blood pressure, the variation in blood pressure at the beginning of dialysis was not very large: in the present series, the mean difference between the two sessions was in fact 8 mmHg (SD 8 mmHg). Consequently, corrections were also relatively small. Besides, blood pressure at the contralateral arm may not accurately represent blood pressure at the shunt side, as has been pointed out [14]. Since in an earlier study [13], much larger blood pressure variations were found, there appears to be substantial differences between various dialysis populations. This is also demonstrated by the mean weight gain between dialyses of 3.8 kg that these authors reported [13], whereas it was only 1.7 kg in our patients and 1.4 kg in another study on shunt flow [11]. With respect to correction of shunt flows for blood pressure, our conclusion is that it should only be recommended if large variations in blood pressure occur.

It appears unlikely that variation in shunt flow occurs due to changes in cardiac output, which are not accompanied by changes in blood pressure. The shunt is a relatively inert conduit of which the resistance cannot be regulated by the body. Therefore, flow changes only occur if the perfusion pressure changes, i.e. the difference between input and output (central venous) pressure. Thus, in the short term, apart from measurement variability and changes in perfusion pressure, shunt flow should remain constant in an individual patient.

The finding that, despite the dispersion of data, Doppler flow values were significantly lower than shunt flow values obtained by ultrasound dilution is also interesting. Some errors in Doppler flow measurements are caused by inaccuracies in estimating the cross-sectional area and by flow variations during the cardiac cycle [15], but one would estimate that these errors contribute to variability but would not cause a systematic difference. Calibration problems should be mentioned here as a possible cause of these findings, but procedures were performed and machines were calibrated as advised by the manufacturers. Another possible source of error may have been that at the measurement site some of the shunt flow had already deviated to collateral veins, although care had been taken to measure in the common flow path. This could have resulted in lower Doppler flow values, as we found, but we can only speculate that this may in fact have been the case.

The duplex flow measurements were done on a location between the arterial and venous puncture sites to obtain the closest approximation to the location of flows measured by ultrasound dilution. It is also the technique with which our technician has most experience. Some authors [16,17] have advocated the use of the brachial artery for this purpose, but convincing evidence for this approach is lacking. The use of the brachial artery has the advantage of a more linear flow pattern than in the shunt itself, and a more perfectly round circumference but, on the other hand, a systematic error due to the inclusion of the blood supply to forearm and hand is introduced. This is why our study measurements were done on the shunt itself. The amount of scatter we found when comparing duplex ultrasound results with ultrasound dilution is comparable with earlier studies [18–20] using various Doppler techniques.

An obvious drawback of the present study is that most of the investigations were not blinded. Only the comparison of ultrasound and Doppler was blinded, since the two technicians performing these measurements were not aware of each other’s results. A way to improve this would have been a design whereby a third technician would have performed the measurements at the second ultrasound dilution session. We did not choose to do this since this would have introduced additional inter-observer variability, which at least in our situation is not clinically relevant, since in our dialysis centre, repeated measurements on the same patient are nearly always done by the same observer.

What are the consequences of these findings for clinical practice? The most relevant consequence appears to be that one should aim for similar needle positions in follow-up flow measurements, especially in radiocephalic fistulas. Even then the variation is so large that the confirmation of a trend by frequently repeated measurements is much to be preferred over a single measurement indicating a decrease in shunt flow. It would probably be wise to also keep all circumstances as constant as possible, i.e. measure at the beginning of dialysis when there is little chance of hypotensive episodes and on the same day of the week so that vascular filling has the best chance of being
similar. If these precautions are taken, and flow is corrected for mean blood pressure, the 95% confidence interval of the difference between shunt flow measurements during two different dialysis sessions (with, in fact, the same flow) is 1.8–18.5%. So, a clinically significant result supporting further action is a flow decrease of more than 20–25%, but only if the measurement circumstances were sufficiently similar. If not, the variation in this method is too large for its clinical use.

References

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