Introduction

I

A. Flow-QC —A New Standard for ESRD Care

In its quest for continuing quality improvement in End-Stage Renal Disease (ESRD) care, the National Kidney Foundation has adopted the Kidney Disease Outcome Quality Initiative (K/DOQI) Guidelines. These guidelines advise proactive management of dialysis patient care and recommend intra-access flow measurement as the preferred method for routine vascular access surveillance. Transonic® Flow-QC Hemodialysis Monitoring gives ESRD care providers an opportunity to better manage their patients with immediate, functional assessments of vascular access patency, hemodialysis adequacy and cardiac function.

1. Vascular Access Patency - A Medical Imperative

As a vascular access fails, it contributes to underdialysis which leads to costly, time consuming surgery that jeopardizes a patient's health. Transonic® Flow-QC Hemodialysis Monitoring tracks a patient's vascular access flow over time and analyzes its historical trend. Because decreases in access flow over time presage access failure, interventions or fistulagrams can be routinely scheduled rather than in response to access failure. Early intervention with minimally invasive flow restorative procedures reduces morbidity and costs.[1] Dialysis administration remains under the control of the clinic. Patient data collection and analysis also remain in house, reducing a dependence on outside services for costly flow studies and lab tests.[2]

[1]McCarley, P., Wingard, R.L., Shyr, Y., Pettus, W., Hakim, R.M., Ikizler, T.A., "Vascular Access Blood Flow Monitoring Reduces Access Morbidity and Costs," Kid Int'l 2001; 60: 1164-1172.
[2]Duda, CR, Spergel, LM, Holland, J, Tucker, T, Bosch, JP, Bander, SJ, "A Multidisciplinary Vascular Access Care Program (VACS) Enables Implementation of Dialysis Outcomes Quality Initiative (DOQI)," JASN 1999; 10: 206A.

2. Hemodialysis Adequacy

An initial Flow-QC program includes a functional assessment of hemodialysis adequacy including:

- verification of delivered blood flow
- detection and quantification of access recirculation
- determination of proper needle placement
- identification of the sources of large negative arterial blood line pressure
  (and its resulting underdialysis)

The immediate report of these tests allows dialysis administration errors to be corrected on the spot, without waiting for lab tests.

Case Study

When Mary Christiensen moved to the senior citizens residence after her husband died, she felt uprooted, having left behind friends and the home she and her husband had shared for 42 years. One constant remained in her new surroundings. Three times a week she would be driven to the nearby dialysis clinic for treatment. Even though she returned to her room drained, she welcomed the treatments because she would feel better for a day or two.

Everyone marveled at Mary's stoicism, for she always projected a brave front. It was only with her chaplain that she confided her terror that, at any given moment, her vascular access could fail.

Her fear was justified. One day she was rushed from the dialysis unit to the hospital for emergency surgery. The first surgery failed, but the second produced a viable access, Mary had a reprieve which gave her a few more months to live. But it was only months, and she was again in the hospital with a failed access. This time she succumbed.

Mary fell victim to sub-standard medical care! The technology for monthly vascular access flow surveillance to predict stenosis was available to the clinic but fiscal priorities had prevented its implementation. Mary's health was compromised and life was shortened because she did not receive routine vascular access surveillance made possible by Transonic Flow-QC.

3. Cardiac Function

Cardiovascular disease (CVD) is the leading cause of morbidity and mortality in ESRD patients. The extent of the disease was reported in a dedicated issue of the American Journal of Kidney Disease. A special report by a task force on CVD entitled "Controlling the Epidemic of Cardiovascular Disease in Chronic Renal Disease" stated that, "after stratification for age, race, and gender, current CVD mortality rates are approximately 10 to 20 times those of the general population."[3] There is ample evidence to suggest that routine Transonic Flow-QC Cardiac Output Monitoring during hemodialysis would significantly improve this statistic.

4. Improved Patient Outcomes

The goal of quality hemodialysis patient care is improved outcomes. Transonic Flow-QC Monitoring enhances outcomes by reducing access failures and morbidity, improving dialysis delivery and extending cardiac function.

[3] Am J Kid Dis 1998; 32(5) Suppl 3.

B. Definition of Terms

Access Flow (AF or Qa)

The rate of blood flow in ml/min passing through the native fistula or artificial graft at the site of the arterial needle.

Access Recirculation (AR)

The percentage of dialyzed blood delivered by the venous needle into the access device that migrates against the direction of the access flow and is removed again by the arterial needle.

Delivered Blood Flow (Qb)

The rate of blood flow in ml/min in the hemodialysis arterial line.

Cardiac Output (CO)

The volume of blood pumped by the heart in a minute, a fundamental measure of human hemodynamic performance in L/min.

Cardiac Index (CI)

Cardiac Output divided by the estimated Body Surface Area.

Central Blood Volume (CBVI)

The volume of blood in the heart, lungs, and the great vessels divided by weight.

Peripheral Resistance (PR)

The average total resistance to blood flow, calculated as mean arterial pressure divided by cardiac output (CO).

C. Indicated Uses

Access Flow Measurement (AF)

- In a patient with a new or revised vascular access:
  Establishes baseline flow, determines its adequacy, and screens for flow rates that are too high.
- In a vascular access surveillance program for a routine patient:
  Proactively identifies the onset of stenosis.
- When access recirculation has been identified:
  Further evaluates the status of the vascular access.

Delivered Blood Flow Monitoring (Qb)

- Verifies pump blood flow when dialysis does not achieve prescribed Kt/V:
  Possible reason target rate may not be met.
- Confirms calibration of dialysis machine:
  When a discrepancy is suspected.
- Verifies close agreement of delivered Qb with prescribed Qb:
  When arterial line pressure is unusually negative due to small needle diameter, high pump setting, arterial needle pointing downstream or needle placement against the wall producing high resistance to flow in the vascular access.

Access Recirculation Measurement (AR)

- Replaces conventional BUN recirculation measurements:
  Provides an immediate and more accurate measure of access recirculation.
- Initial quality assurance on patients with new or revised vascular access:
  Confirms needle placement with respect to flow in the vascular access.
- Test for optimal delivered blood flow for catheter patients:
  Confirms optimal delivery of dialysis if no recirculation is present.
- Access patency measurement:
  Confirms that flow in the access stays above the dialysis pump setting.

C. Indicated Uses *cont.*

Cardiac Function Measurement (CO, CI, CBV)

- Monitors dangerously high levels of cardiac output:
  High access flow places abnormal stress on the heart, which can cause cardiomegaly and heart failure.
- Monitors dangerously low levels of cardiac output:
  Weak cardiac function places patients at high risk for cardiovascular complications and failure.
- Monitors dramatic decrease of Cardiac Index during hemodialysis to dangerously low levels due to inaccurate dry weight estimation and/or inadequate medication:
  These patients are at high risk for cardiovascular complications and failure.
- Monitors dangerous decrease in Central Blood Volume during dialysis:
  These patients are placed at risk for hypotensive episodes.

The Technology
Behind the Measurements

II

A. Transonic Flow-QC System

The Transonic Flow-QC Hemodialysis Monitoring System consists of an ultrasonic blood property monitor, a set of matched flow/dilution sensors, a laptop computer, a data analysis software package and a rolling stand. This self-contained, compact system can be moved from patient to patient during routine dialysis treatments.

MONITOR: The Flow-QC Monitor processes information collected from the flow/dilution sensors before sending it to the laptop computer for analysis and display. The monitor and laptop computer communicate with each other through a serial cable. The monitor also displays ultrasound signal strength and delivered blood flow.

COMPUTERIZED DATA ANALYSIS: The software records, stores and displays dilution curves, measurement values, historical graphs and detailed reports. It also has the capability of documenting interventions and identifying patients at risk for thrombosis, and produces clinic and patient statistics.

SENSORS: Precision ultrasound flow/dilution sensors detect patient blood property data. One sensor is clipped to the venous blood line and the other to the arterial blood line with a small amount of petroleum jelly serving as ultrasound couplant.

B. True Delivered Blood Flow (Qb)

Transonic's "gold standard" ultrasound transit-time flow technology is used to verify the true blood flow being delivered by the dialysis machine. Each sensor emits an ultrasound beam which travels through the tubing and blood both in upstream and downstream directions (Fig. 1). When the ultrasound beam travels in the direction of flow, the time it takes for the beam to traverse the distance through the tubing and blood (the transit-time) is decreased by a flow-dependent amount. When the beam travels in the opposite direction, against the flow in the tube, the beam's transit time is increased by a flow-dependent amount. By subtracting upstream and downstream transit-times, volume flow is calculated.

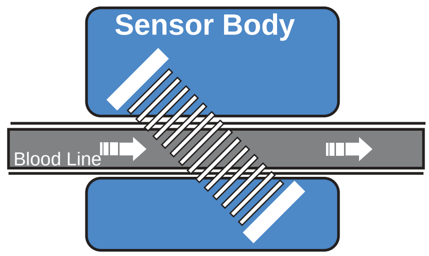

Fig. 1: Blood line inserted into the groove of the flow/dilution sensor body. Direction of flow is indicated by arrows. Ultrasound beam is shown emanating from one of four transducers in the sensor body.

C. Access Recirculation (AR)

The clip-on flow/dilution sensors also monitor the ultrasound velocity in blood. Ultrasound travels at 1560 to 1590 m/sec in blood. This velocity is determined primarily by the blood protein concentration: the greater the protein concentration, the faster ultrasound will travel. By introducing a bolus of isotonic saline (1533 m/sec) into the blood, the protein concentration is diluted and the ultrasound velocity is decreased. The reduced ultrasound velocity is recorded by the flow/dilution sensors and monitor. When Access Recirculation exists, saline will immediately flow back into the

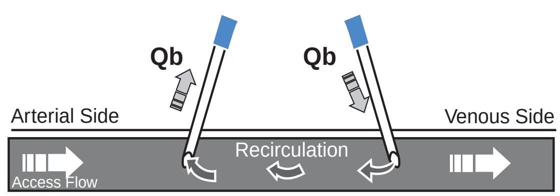

Fig. 2: Access recirculation : backflow through the vascular access into the arterial needle.

arterial line as shown in Figure 2. Transonic Flow-QC software converts the data into two conventional dilution curves, the first representing the saline dilution as flow passes the venous sensor and the second representing the saline dilution as flow passes the arterial sensor. Recirculation is calculated as a ratio of the area under the arterial curve to the area under the venous curve (Fig. 3).

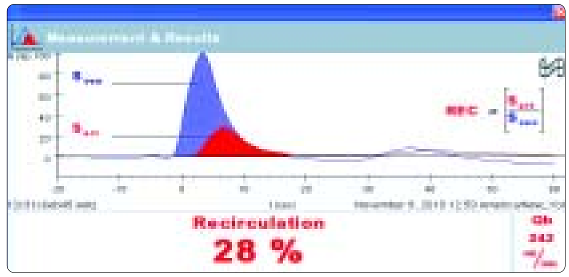

Fig. 3: A blue venous (upper) dilution curve followed by a red (lower)arterial curve. The ratio of the areas under the curves indicates 19% recirculation.

Recirculation foreshadows a failing access and generally occurs when access flow (AF) is less than dialysis pump flow (Qb). Because Transonic ultrasound dilution technology is able to separate actual vascular access recirculation from cardiopulmonary recirculation (Fig. 4), measurement of zero percent access recirculation (0%AR) as shown in Figure 5 has become a reality.[4,5] Measurement technologies which cannot separate these two recirculations always show a false positive recirculation due to the presence of the cardiopulmonary recirculation.

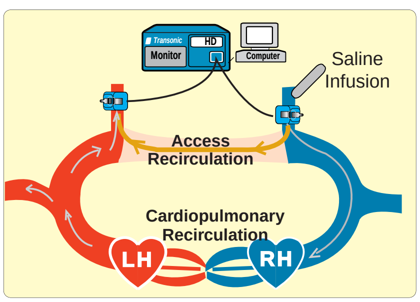

Fig. 4: Schematic showing routes of vascular recirculation and cardio-pulmonary recirculation.

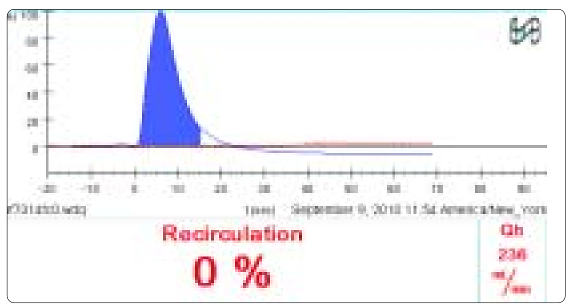

Fig. 5: The dilution curve above shows a blue venous dilution curve but no significant red arterial curve indicating 0% Recirculation.

[4]MacDonald, J., Sosa, M., Krivitski, N.M., Glidden, D., Sands, J.J., "Identifying A New Reality: Zero Vascular Access Recirculation Using Ultrasound Dilution," ANNA J 1996;23(6): 603-608.

[5]Alloatti, S., Molino, A., Bonfant, G., Ratibondi, S., Bosticardo, G.M., "Measurement of Vascular Access Recirculation Unaffected by Cardiopulmonary Recirculation: Evaluation of an Ultrasound Method," Nephron 1999;81: 25-30.

D. Access Recirculation (AR) *cont.*

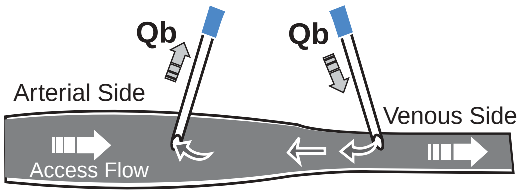

Fig. 6: Access recirculation caused by venous stenosis. A portion of the dialyzed blood recirculates from the venous needle back into the arterial needle.

Figure 6 shows the typical flow of blood in a patient with recirculation due to a venous stenosis. Access flow is not adequate for the demands of the pump setting. Lack of flow at the arterial needle is compensated for by reclaiming some part of the freshly dialyzed blood from the venous line.

There is one important exception to the rule that recirculation (AR) usually occurs when access flow (AF) is less than dialysis pump flow (Qb). This unique situation exists when there is a stenosis between the needles (Fig. 7). Because the stenosis limits flow through the access, the pump simply bypasses the stenosis (area of greatest hydrodynamic resistance). In this case zero recirculation (0%AR) can be reported although access flow (AF) is less than delivered blood flow (Qb).

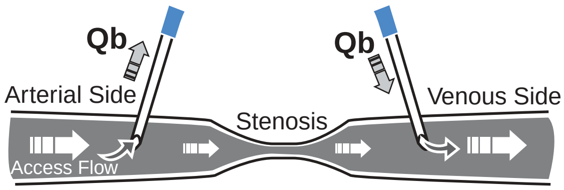

Fig. 7: The paradoxical situation when there can be 0% recirculation although access flow is less than delivered blood flow. A mid-graft stenosis limits access flow. Pump flow (Qb) bypasses the stenosis.

When Flow-QC monitoring first indicates vascular access recirculation but the recirculation disappears after the blood lines are reversed, the hemodialysis lines have been inadvertently reversed. Published data show that dialysis occurs with the needles inadvertently reversed in 4-20% of cases.

D. Access Flow (AF)

Access Flow measurements are performed using the Krivitski Method® by reversing the blood lines at the needle connections. The dialyzer now removes blood from the venous side of the access and returns it to the arterial side (Fig. 8). This creates mixing conditions which the Krivitski Method uses to make an indicator dilution measurement of access flow.

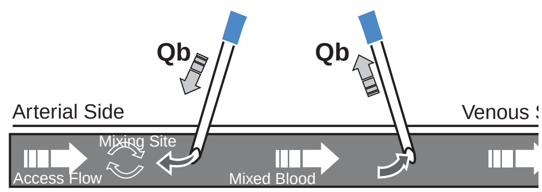

Fig. 8: Hemodynamics of access flow measurement with lines reversed according to the Krivitski Method. Line reversal creates an artificial recirculation loop with a mixing site at the arterial side of the access.

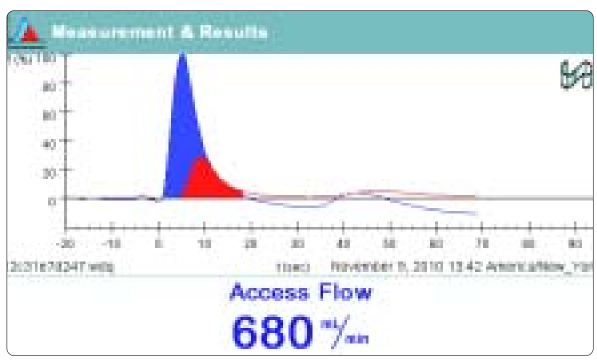

Fig. 9: Results of an access flow measurement showing 680 ml/min flow.

By introducing saline into the venous line in the same manner and into the same injection port as for access recirculation measurements, blood protein concentration is diluted and ultrasound velocity is reduced. This change in blood protein concentration is detected by the venous line sensor, producing the blue dilution curve (Fig. 9). The diluted blood from the venous line then enters the access and mixes with the incoming access flow. Upon reaching the arterial needle, a portion of mixed blood is removed from the access by the dialyzer, via the venous needle. The diluted blood is detected by the arterial line sensor producing a red dilution curve (Fig. 8). Access flow is calculated from the ratio of the area under the venous curve to the area under the arterial curve.

E. Cardiac Output (CO)

Indicator dilution in systemic flow provides a measure of cardiac output when blood lines are connected in the normal configuration and there is no direct vascular access recirculation (Fig. 4). In this instance, the complete saline indicator bolus travels into the heart where it mixes with (is diluted into) the full volume of blood leaving the heart. Part of this diluted indicator then reappears at the arterial sensor. Cardiac output is calculated via conventional Stewart-Hamilton analysis. Flow-QC software permits entry of additional patient data to calculate:

- **Cardiac Index (CI):** cardiac output divided by the estimated Body Surface Area (BSA).

- **Peripheral Resistance (PR):** the average resistance to systemic blood flow and is approximated as mean arterial pressure divided by cardiac output.

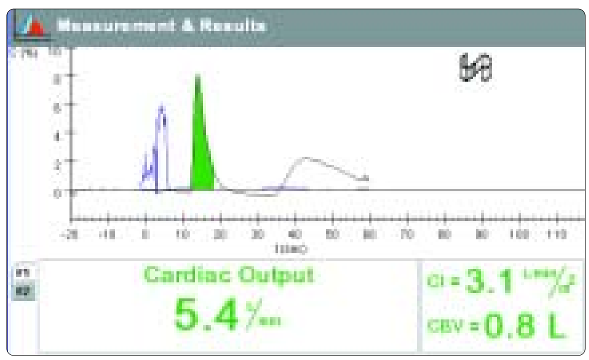

Fig 10: Results of an cardiac function measurement. showing cardiac output at 5.4 L/min; CI at 3.1 L/min/m^2 and CBV at 0.8L.

- **Central Blood Volume (CBV) and Central Blood Volume Index (CBVI):**
  the volume of blood in the heart, lungs, and the great vessels.
  CBVI is CBV divided by weight.

Please refer to the Transonic companion booklet *"Cardiac Function Assessment during Hemodialysis"* for additional information about Flow-QC Cardiac Function Protocols.

K/DOQI Guidelines

III

The goal of the National Kidney Foundation's K/DOQI Guidelines is to improve hemodialysis outcomes through best clinical practices. Based on the collective expertise of the committee and on published scientific studies, the guidelines target improvements in dialysis adequacy and maintenance of patent, healthy vascular accesses.

A. Kt/V Dose

K/DOQI guidelines recommend a delivered dose of hemodialysis with Kt/V of at least 1.2 or a URR of 65%, noting that these values are associated with low rates of patient morbidity.[6] The committee outlines instances when this delivered dose may not be met. Compromised urea clearance is one cause. Urea clearance may be compromised by many factors, including access recirculation, inadequate vascular access flow, blood pump calibration errors, and inadequate dialyzer reprocessing.

When Kt/V falls below these prescribed levels, the source of the inadequacy should be examined. K/DOQI guidelines state "hemodialysis units and clinicians should strive to categorize failures and to identify specific causes,…"[7] The Hemodialysis Adequacy Guidelines present an Error Analysis Algorithm, which suggests possible problems. It is recommended that the machine's maintenance log be checked for the last calibration date and results, as well as

[6,7]National Kidney Foundation. K/DOQI Clinical Practice Guidelines for Hemodialysis Adequacy, 2000.Am J Kidney Dis 2001; 37 Suppl 1: S7-S64.
National Kidney Foundation. DOQI Clinical Practice Guidelines for Hemodialysis Adequacy, 1997. Am J Kidney Dis 1997; 30(3)Suppl 2: S46.

checking for large negative arterial line pressures. The blood pump may be out of calibration or the negative line pressure may affect pump delivery. The access itself should be checked for recirculation. The A/V needle placement should be reviewed and the access flow configuration verified. This is done to make sure that the lines have not been inadvertently reversed, which may occur when there is confusion about the direction of flow in the access. Although the guidelines suggest, "It is unrealistic to expect that dialysis care teams to immediately identify and correct problems that result in inadequate hemodialysis,"[8] Transonic Flow-QC Monitoring overturns this assumption by providing the capability to identify, correct, and/or rule out many problems that result from inadequate hemodialysis. The Transonic Flow-QC program, described in Chapter 3, checks all of these possibilities in an initial dialysis adequacy study.

B. Vascular Access Conditions

Conditions within the vascular access itself play a large role in the delivery of adequate dialysis. Access recirculation and access flow are two parameters which may effect the delivery of the prescribed treatment. The vascular access is fundamental to a ESRD patient's well being. It is their "link to life" and influences the patient's quality of life. Frequent complications, clotting, and the procedures to correct these problems compromise the patient's ability to live a normal life. K/DOQI guidelines note that trends of decreasing access flow are predictive of stenosis. The guidelines recommend monitoring access flow to detect the early onset of stenosis and reduce the occurrence of failure. The K/DOQI Clinical Practice Guidelines for Vascular Access state that, "early detection and treatment of stenosis reduces the frequency of thrombosis and reduces replacement rates by up to 70%."[9]

[8]Ibid.
[9]AJKD 1997; 30(4)Suppl 3: S180, S164.

C. Direct Access Flow Measurement

The K/DOQI Guidelines also state, “Direct flow measurements, if available, are preferable compared to more indirect measures (Evidence).”[10] Access Recirculation has been found to be a relatively late predictor of access dysfunction. By the time Access Recirculation presents, the flow limiting stenosis has progressed to a point where flow restorative procedures will not be effective. Access Recirculation signals that access flow is insufficient to maintain the prescribed Qb: some portion of freshly dialyzed blood must recirculate in order to meet the set Qb. The K/DOQI guidelines also point out that, “in primary AV fistulae, inadequate flow through the access is the primary functional defect predictive of thrombosis and access failure.”[11] Indirect measurements of access flow are not an effective monitoring tool. According to Dember et al., venous pressure monitoring is ineffective in identifying problematic stenosis in AV fistulae.[16] Doppler flow studies are less attractive for access flow monitoring due to their cost and because the results are observer dependent. The Transonic Flow-QC Hemodialysis Monitor provides a simple and inexpensive means to measure access flow.

D. Monitoring Recommendations

The K/DOQI guidelines recommend monitoring at intervals of at least once a month to diagnose the onset of stenosis. These monthly measurements should be, “…tabulated and tracked within each dialysis center as part of a Quality Assurance/Continuous Quality Improvement program”[12] and evaluated to look for trends toward decreases in flow. Proactive identification of access stenosis should be followed by expeditious referral for corrective procedures. When the

[10] Ibid.
[11] Dember, L.M., Holmberg, E.F., Kaufman, J.S., “Value of Static Venous Pressure for Predicting Arteriovenous Graft Thrombosis”, Kid Int'l 2002; 61: 899-1904. (HD303)
[12] Am J Kid Dis 1997; 30(4) Suppl 3: S180, S164.

onset of stenosis is detected well in advance of failure, minimally invasive procedures can be used to correct the problem. It allows more freedom in scheduling the procedure, reduces loss of treatment time, minimizes costs, and creates greater peace of mind for the patient. The Transonic Flow-QC Monitoring program, as presented in the next section, integrates K/DOQI recommendations into a clinic’s routine quality care schedule.