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ORIGINAL ARTICLE

# Hemodialysis catheter tip design: observations on fluid flow and recirculation

**Thomas M. Vesely[1], Adrian Ravenscroft[2],**

[1] Vascular Access Services, LLC, Saint Louis, Missouri - USA
[2] Phase One Medical, Hingham, Massachusetts - USA

## ABSTRACT

**Purpose:** To observe fluid flow patterns and measure recirculation rates of tunneled hemodialysis catheters using a mechanical model that simulates hemodialysis treatment.

**Materials and methods:** Nine tunneled hemodialysis catheters were evaluated using a mechanical model that simulated catheter conditions during a routine hemodialysis treatment. Objective and subjective determinants of catheter performance were measured and compared. Catheters were evaluated with blood lines connected in standard and reversed configurations using a fluid flow rate of 425 ml/min.

**Results:** With blood lines in standard configuration the Split Cath® was the only catheter to exhibit an atypical fluid flow pattern and significant tip movement. When the blood lines were reversed, three split-tip catheters had significant tip movement. The three step-tip catheters and two symmetric tip catheters had stable fluid flow patterns and no significant tip movement with blood lines connected in standard and reverse configurations.
The nine catheters had no recirculation when connected in standard configuration. When the blood lines were reversed the percentage of recirculating fluid for symmetric tip, step-tip, and split-tip catheters was 0%, 15% to 20%, and 20% to 30%, respectively. The Equistream®, Palindrome™, and Symetrex catheters had no recirculation with blood lines connected in standard or reversed configurations.

**Conclusions:** Eight of the nine catheters evaluated in this study performed well with blood lines connected in standard configuration. When blood lines were reversed, symmetric tip and step-tip designs had more stable fluid flow patterns, less tip movement and lower recirculation rates when compared to split-tip designs.

**Keywords:** Central venous catheter, Vascular catheter, Vascular access devices

## Introduction

The majority of patients requiring long-term renal replacement therapy will begin hemodialysis treatment using a tunneled hemodialysis catheter (1). A tunneled hemodialysis catheter is a dual lumen, large diameter (14-16 French), polyurethane catheter with an annular fibrous cuff (2). Hemodialysis catheters can be differentiated by the design of the distal tip (3). The distal tip can be simple, such as a step-tip catheter with no side holes, or complex, such as a tapered, split-tip catheter with multiple side holes (4). Other common features include guidewire holes and flow dividers. The hemodynamic effects of these different tip designs remain largely unknown and often debated.

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**Corresponding author:**
Thomas M. Vesely
24 The Boulevard Saint Louis
Unit 420, Saint Louis
63117 Missouri, USA
tmvesely@gmail.com

Clinical comparison of different catheter tip designs is difficult because catheter performance is influenced by factors that are unrelated to tip design (5). The technique of catheter insertion, the location of the distal tip, even the diligence of the hemodialysis technician can influence catheter performance. One important measure of hemodialysis catheter performance is its ability to provide the prescribed hemodialysis treatment. Other objective measures of clinical performance include the rate of blood flow, the percentage of recirculated blood, and the arterial and venous pump pressures needed to achieve the prescribed blood flow rate (6-8).

The performance of a tunneled hemodialysis catheter can also be evaluated using non-clinical test systems that simulate hemodialysis treatment. Computational models and mechanical models can provide uniform test conditions to compare different features of catheter tip design (9, 10). Fluid flow patterns, shear stress and hydraulic resistance have been measured using hemodialysis simulation models (11, 12). However, results obtained using computational or mechanical models may not replicate clinical results obtained in a patient undergoing chronic hemodialysis treatment. This is a recognized limitation of non-clinical test methods (3).

The purpose of this study was to observe, characterize, and measure fluid flow patterns occurring at the distal tip of

nine different tunneled hemodialysis catheters. The catheter testing system was a bench-top mechanical model that replicated the anatomic dimensions of the central veins, the fluid viscosity of blood, and the blood flow rates that occur during a typical hemodialysis treatment. The design of the mechanical model provided the investigators with direct observation of the fluid flow patterns occurring at the distal tips of nine different hemodialysis catheters.

## Materials and methods

Nine tunneled hemodialysis catheters were subjectively and objectively evaluated using a bench top mechanical model that simulated conditions of a routine hemodialysis treatment. Subjective observations of distal tip fluid flow patterns were made by two independent observers and documented with digital photography and videography. The objective parameter of catheter performance was the percentage of recirculating fluid when measured with blood lines connected in both standard and reversed configurations. Each hemodialysis catheter was evaluated using two different fluid viscosities; the viscosity of water (1.0 cP) and the viscosity of blood with a hematocrit of 40% (2.3 cP) (13).

### *Hemodialysis catheters*

Nine hemodialysis catheters with different tip designs were evaluated (Tab. I). All are polyurethane, dual-lumen catheters with an annular fibrous retention cuff. Catheter diameter ranged from 14 French to 16 French and catheter length ranged from 19-33 cm. The nine hemodialysis catheters were divided into three groups based upon distal tip design; three step-tip catheters, four split-tip catheters, and two symmetric-tip catheters.

*Step-tip catheters*

The three step-tip catheters had similar tip designs with a round venous end hole, a D-shaped arterial end hole, and two round side holes in the distal tip of the venous lumen (Tab. II). The A/V offset is defined as the length of separation between the arterial and venous end holes (Fig. 1). The Ultrastream™

**TABLE I -** Design features of the nine tested hemodialysis catheters

| Name | Size | Length | Tip design | A/V offset | Sideholes | Split length |
|---|---|---|---|---|---|---|
| ProGlide™ | 14.5 | 19 cm | Step | 30 mm | Yes | |
| Titan™ | 15.5 | 24 cm | Step | 25 mm | Yes | |
| Ultrastream™ | 15.5 | 28 cm | Step | 20 mm | Yes | |
| Ash Split® | 14 | 28 cm | Split | 30 mm | Yes | 80 mm |
| Centros® | 15 | 24 cm | Split | 25 mm | No | 25 mm |
| Hemosplit® XK | 16 | 23 cm | Split | 30 mm | Yes | 45 mm |
| Equistream® | 16 | 27 cm | Split | 12 mm | Yes | 43 mm |
| Palindrome™ | 14.5 | 19 cm | Symmetrical | 11.5 mm | Yes | |
| Symetrex | 15.5 | 33 cm | Symmetrical | None | No | |

**TABLE II -** Description of side holes in the nine tested hemodialysis catheters

| Name | Arterial side holes | Venous side holes |
|---|---|---|
| ProGlide™ | No | Two 1.25 mm holes |
| Titan™ | No | Two 1.25 mm holes |
| Ultrastream™ | No | Two 1.0 mm holes |
| Split Cath® | Three pairs of 1.25 mm side holes + one 1.25 mm × 2.75 mm oval | Two pairs of 1.0 mm holes |
| Centros® | No | No |
| Symetrex | No | No |
| Hemosplit® XK | Four 1.0 mm holes | No |
| Equistream® | One 2 mm × 4 mm oval hole + three 1.25 mm holes | No |
| Palindrome™ | Yes | One 1.65 mm trapezoidal hole |

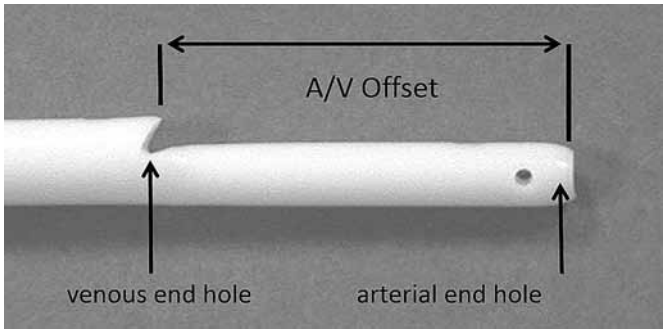


**Fig. 1 -** Measurement of A/V offset.

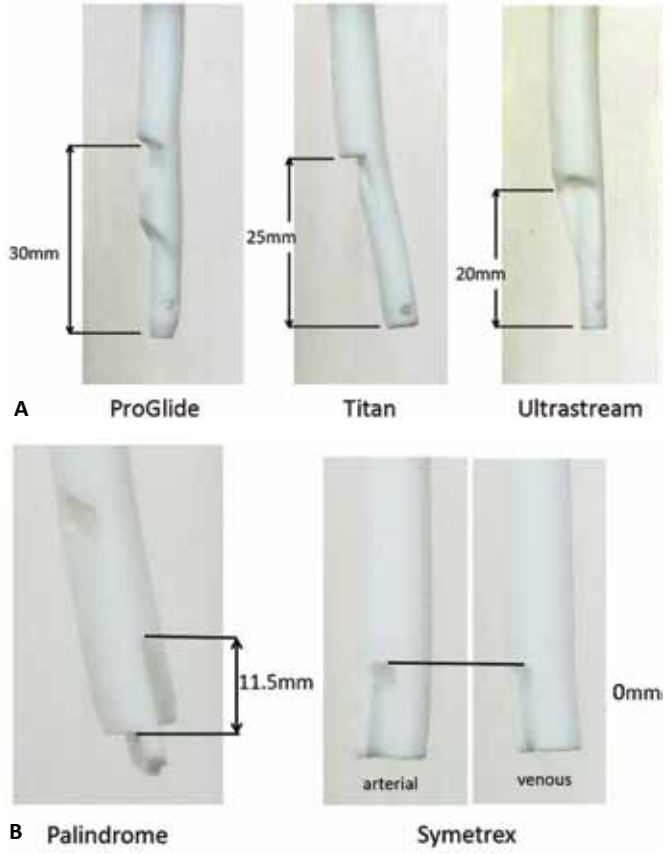


**Fig. 2 -** (**A**) A/V offset of step-tip catheters. (**B**) A/V offset of symmetric-tip catheters.

(Argon Medical. Plano, TX), Titan™ (Medcomp. Harleysville, PA) and ProGlide™ (Merit Medical. South Jordan, UT) catheters have 20 mm, 25 mm, and 30 mm of A/V offset, respectively (Fig. 2A). The Ultrastream™, Titan™, and ProGlide™ catheters each have two small (1.0 mm-1.25 mm) round side holes positioned 3.0 mm, 2.5 mm and 5.0 mm, respectively, from the venous end hole. None of these three step-tip catheters have side holes along the arterial lumen. The Ultrastream™ has a thin (1.2 mm) horizontal flow barrier separating the midline of the arterial end hole (Fig. 3). The ProGlide™ has a thick vertical flow barrier separating the arterial and venous end holes. The Titan has a low profile (1.0 mm), V-shaped, beveled ramp in front of the arterial end hole.

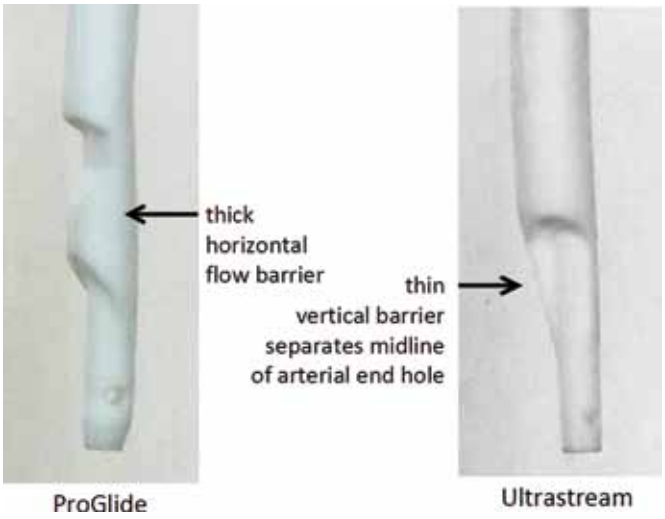


**Fig. 3 -** Step-tip flow barrier designs.

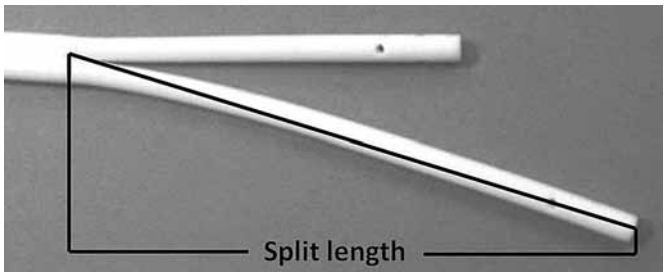


**Fig. 4 -** Measurement of split length.

*Split-tip catheters*

The four split-tip catheters have similar tip designs with D-shaped venous and arterial lumens. The Ash Split® (Medcomp. Harleysville, PA) and Equistream® (Bard Access. Salt Lake City, UT) have straight-cut end holes. The Hemosplit® XK (Bard Access. Salt Lake City, UT) and Centros® (Angiodynamics. Queensbury, NY) catheters have angled-cut end holes. The Equistream® has one large and three small oval side holes along the distal tip of both the arterial lumen and venous lumens (Tab. II). The two curved limbs of the Centros® catheter do not have side holes. The Ash Split® has three pairs of two helically spaced oval side holes along the distal tip of the arterial lumen. There are two pairs of two helically spaced oval side holes along the distal tip of the venous lumen. The Ash Split also has an oval guidewire hole in the distal tip of the venous lumen. The Hemosplit® XK has four round helically spaced side holes along the distal tip of the arterial lumen and two round helically spaced side holes along the distal tip of the venous lumen.

The split length is defined as the distance from the apex of the split limbs to the distal tip of the longest limb, typically the venous limb (Fig. 4). The Centros®, Equistream®, Hemosplit® XK, and Ash Split® catheters have split lengths of 25 mm, 43 mm, 45 mm and 80 mm, respectively (Fig. 5). The Ash Split® and Hemosplit® XK catheters have narrow

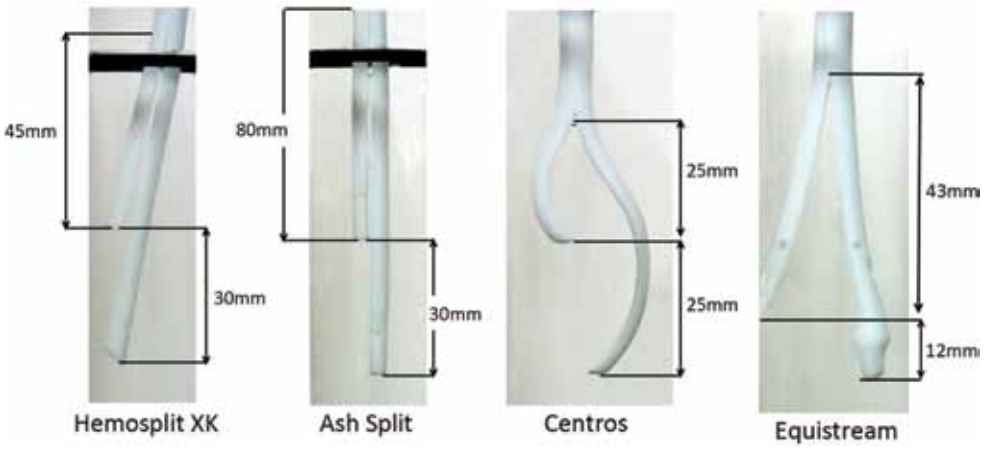


**Fig. 5 -** Split lengths of split-tip catheters.

separation (1 mm-3 mm) of parallel arterial and venous limbs. The Equistream® and Centros® have wider separation (10 mm-12 mm) of the arterial and venous limbs. The two split limbs of the Centros® are uniquely curved and the venous limb is twice the length (50 mm) of the arterial limb (25 mm).

A unique feature of the Ash Split® is tapering of the inner lumen along the distal tip. Both limbs of the Ash Split® have D-shaped lumens that change to circular lumens with a smaller (1.8 mm) cross section at the distal tip. A unique feature of the Equistream® is the bulbous tip of the venous limb. The end hole in this bulbous tip is a guidewire hole not in continuity with the venous lumen. The venous (outflow) lumen of the Equistream® exits through a slanted (2 mm × 4 mm) slot in the lateral wall of the split venous limb. This venous outflow slot is positioned 18 mm from the guidewire end hole in the bulbous tip.

*Symmetric-tip catheters*

The Tal Palindrome™ (Covidien. Mansfield, MA) catheter has a thin horizontal septum separating the arterial and venous lumens. This septum extends 5 mm beyond the triangular-shaped end holes. The Palindrome™ has one trapezoidal-shaped side hole in the distal tip of both the arterial and venous lumen. The arterial and venous limbs of the Symetrex catheter (Phase One Medical. Hingham, MA) are equal lengths; the distal end is flat with no A/V offset (Fig. 2B). There is an arched 2 mm x 8.5 mm horizontal slot along the distal tip of both the arterial and venous limbs.

***Catheter testing system***

The catheter testing system is a bench-top mechanical model that simulates conditions found during routine hemodialysis treatment (Fig. 6). The mechanical model simulated the blood flow rate and anatomic dimensions of the superior vena cava, the blood flow rate through the hemodialysis catheter, and the blood viscosity of a hemodialysis patient (6, 14-17).

The catheter testing system consisted of three independent fluid pathways; 1) the superior vena cava, 2) the venous lumen of the hemodialysis catheter and, 3) the arterial lumen

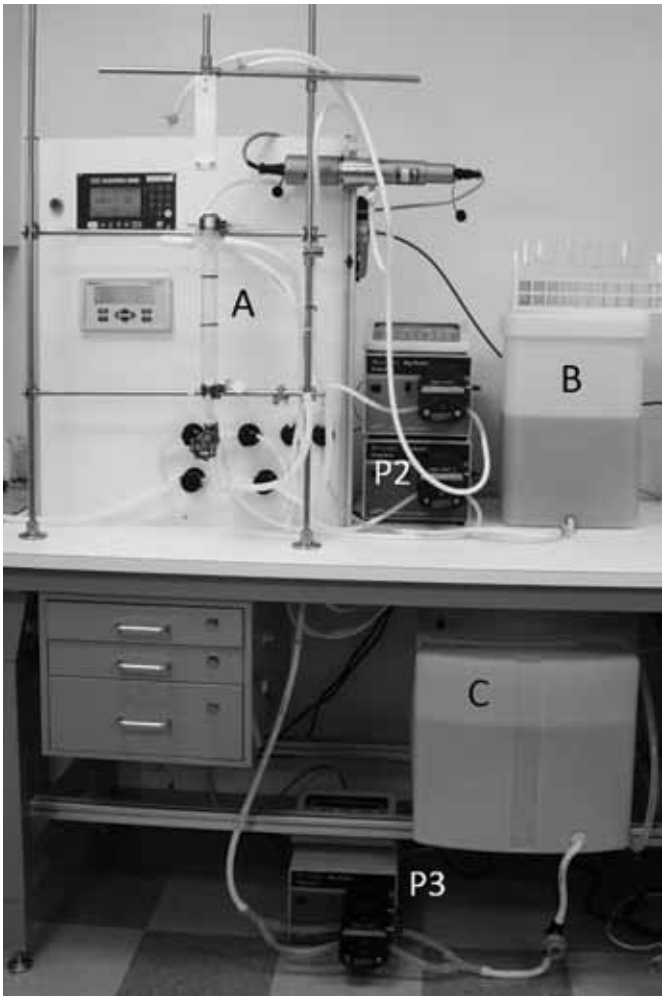


**Fig. 6 -** Bench top mechanical model for testing hemodialysis catheters. (**A**) glass column observation chamber; (**B**) blue dye tank; (**C**) primary tank. **P2** and **P3** are dual-channel peristaltic fluid pumps.

of the hemodialysis catheter (Fig. 7). The fluid pathways were constructed using Masterflex® silicone tubing with 1/4-inch internal diameter (Cole-Parmer, Vernon Hills, IL). The 3-circuit design allowed independent control of the rate of fluid flow

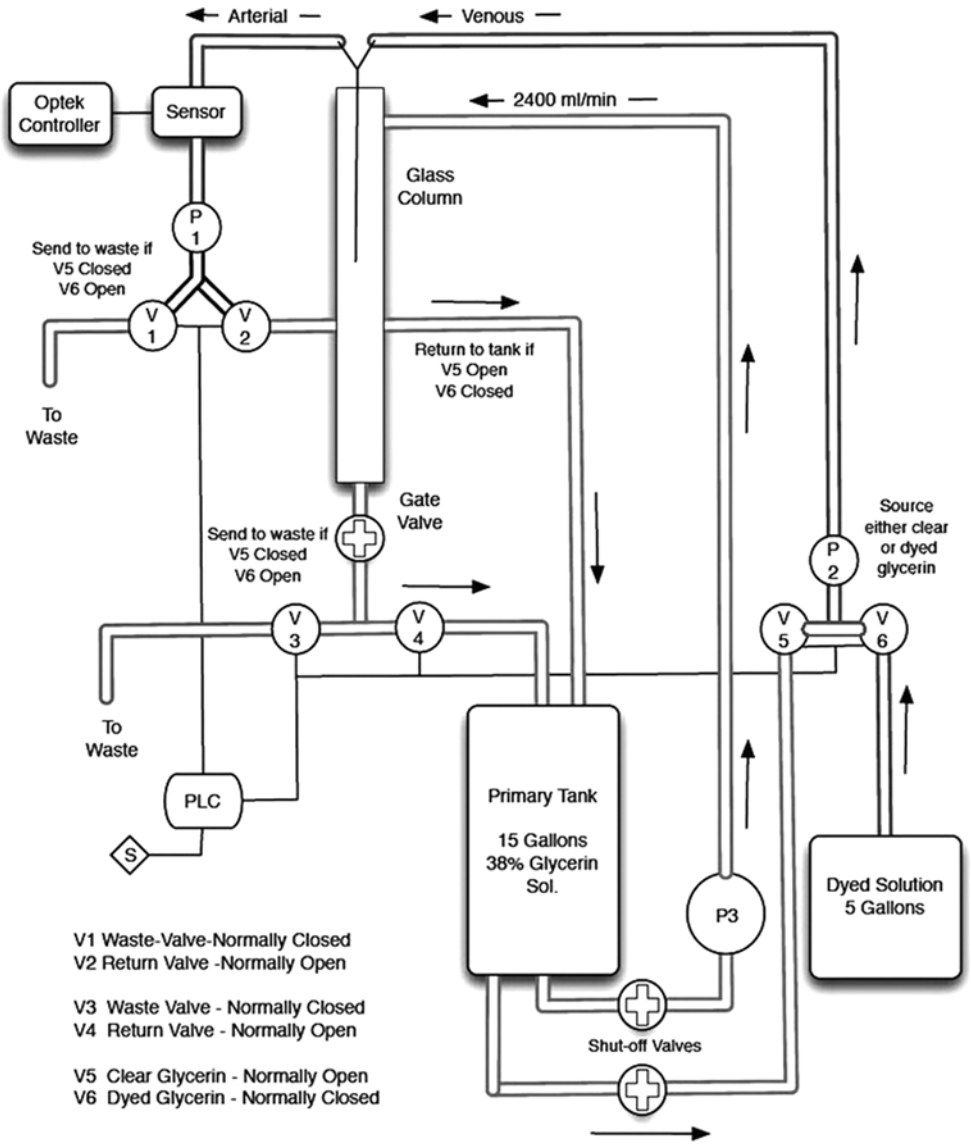


**Fig. 7 -** Schematic drawing of three pathways of fluid flow through mechanical model.

and the direction of fluid flow through both lumens of the hemodialysis catheter and through the simulated superior vena cava.

Fluid flow through the three independent circuits was generated by three (P1, P2, P3) dual-channel peristaltic pumps (Digi-Staltic, Masterflex®, Cole-Parmer, Vernon Hills, IL) (Fig. 7). Each pump was independently controlled by the programmable logic controller unit (PLC) (Moeller Electric, Cologne, Germany). Fluid was pumped (P2) from the primary tank to the glass column through the venous lumen of the hemodialysis catheter at a rate of 425 ml/min. Fluid was aspirated (P1) from the glass column through the arterial lumen at a rate of 425 ml/min. The rate of fluid flow through the glass column was maintained at 2400 ml/min by the peristaltic pump (P3).

The direction of fluid flow through the three independent circuits was controlled by six air-activated valves (Acro Associates, Concord, CA) located at junctions along the silicone tubing. The six valves were sequentially actuated by the PLC unit according to the test protocol. This feature enabled testing of each hemodialysis catheter with fluid flowing in both directions simulating blood lines connected in standard and reversed configurations.

The distal half of the catheter was vertically suspended in a glass column (24 mm × 350 mm) that simulated the anatomic dimensions of a superior vena cava (Fig. 8) (14, 15). There was laminar fluid flow through the glass column and the top was open to ambient air pressure. Normal venous pressure in the superior vena cava ranges from 3 mm Hg-8 mm Hg (17, 18).

To simulate this pressure, the distal tip of the test catheter was precisely positioned below the fluid surface in the glass column. The glycerin solution (38% wt/wt) pumped through the circuits had a specific gravity of 1091.80 kg/mg$^3$ at 25°C. Using this value it was calculated that each 1 mm depth of 38% glycerin solution applies 0.08 mm Hg of pressure inside the glass column (19). Therefore, during testing the distal tip

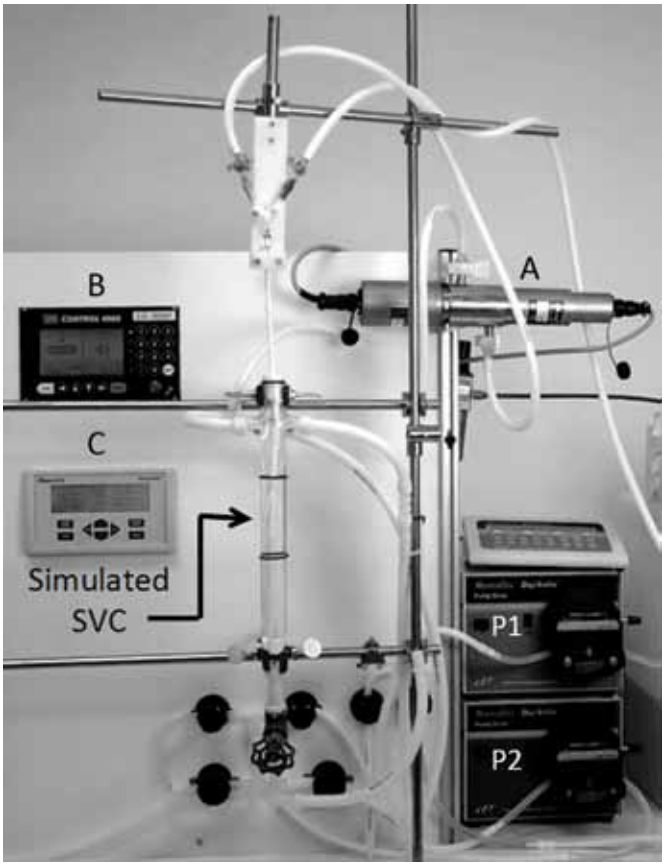


**Fig. 8 -** Vertical orientation of catheter tip in glass column, the simulated superior vena cava. (**A**) dual-channel optical sensor; (**B**) optical sensor control unit; (**C**) programmable logic controller unit. **P1** and **P2** are dual-channel peristaltic fluid pumps.

of each catheter was positioned 100 mm below the surface of the fluid column to approximate a pressure of 8 mm Hg within the superior vena cava. A brass spigot valve located at the bottom of the glass column was used to equilibrate the fluid flow to stabilize the fluid level in the glass column during the catheter testing procedures.

A 15-gallon primary tank holds the 38% glycerin solution that was pumped through the three circuits of the mechanical model (Fig. 6). A 5-gallon secondary tank held a solution of 38% glycerin plus blue indicator dye in water that was used for colorimetric measurement of catheter recirculation. A valve (V6) actuated by the PLC regulated the flow of blue indicator dye into the venous lumen of the hemodialysis catheter (Fig. 7). A preservative (0.1% Kathon™ CG/ICP) (Dow Chemical, Midland, MI) was added to the stored glycerin solutions.

***Recirculation***

The percentage of recirculating blood, the fluid exiting the outflow lumen that is aspirated into the inflow lumen, was measured using an optical indicator dye method. The 5-gallon secondary tank held a precise concentration of blue indicator dye solution; 0.065 grams of blue dye concentrate (Cole-Parmer 00298-18, Vernon Hills, IL) mixed in 1000 grams of 38% water-glycerin solution to achieve a fluid viscosity of 2.3 cP. The viscosity of the blue dye solution was verified using the Brookfield DV-E viscometer.

The PLC controlled the timing and rate of release of blue indicator dye into the venous (outflow) lumen of each catheter during the testing protocol. Indicator dye aspirated into the arterial (inflow) lumen was detected by a dual-channel optical sensor (Optek C-4000 with AF26 sensor; Optek-Danulat, Inc. Germantown, WI) located along the arterial circuit of the mechanical model (Fig. 8). The optical sensor was calibrated using serially diluted dye solutions to create absorption linearization tables for wavelengths of 620 nm and 800 nm. During the catheter testing protocol the blue dye that was aspirated into the arterial lumen was discarded into a waste container; the blue indicator dye did not return to the primary storage reservoir.

***Catheter testing protocol***

The nine hemodialysis catheters underwent identical testing procedures. The hemodialysis catheter was vertically suspended in the glass observation column with the distal tip positioned 100 mm below the fluid surface. The fluid flow rate through the observation column, the simulated superior vena cava, was 2400 ml/min. The flow rate through the arterial and venous lumens was 425 ml/min during all testing procedures.

Each catheter was tested with the simulated blood lines connected in both standard and reversed configurations. Standard configuration is the arterial (inflow) blood line connected to the arterial (red) Luer hub of the catheter and the venous (outflow) blood line connected to the venous (blue) Luer hub of the catheter. When the blood lines are connected in reversed configuration the inflow blood line is connected to the blue Luer hub and the outflow blood line is connected to the red Luer hub of the hemodialysis catheter.

The testing period was 30 seconds in duration. The sequencing of valve positions and pump activation was managed by the programmable logic controller unit. Upon initiation of the test protocol there was a 5-second flushing period to allow complete filling of the silicone tubing and stabilization of fluid flow through the three independent circuits. The 25-second observation period started when the PLC released blue dye into the outflow (venous) lumen of the hemodialysis catheter. The blue dye flowed through the venous lumen and into the glass column, the simulated superior vena cava. Any blue indicator dye aspirated into the inflow (arterial) lumen was detected and measured by an optical sensor positioned along the arterial circuit (Fig. 3). Catheter tip recirculation was measured at the end of the 30-second test sequence. During each 30-second test sequence the blue indicator dye aspirated into the inflow (arterial) lumen was routed to a discard container. The blue dye did not reenter the circuit. Following each test sequence the three circuits were flushed with 38% glycerin solution for 20 seconds to clear residual blue dye.

The nine hemodialysis catheters underwent 72 testing procedures. Each catheter was tested using; 1) water with a measured viscosity of 1.0 cP and, 2) a glycerin-water solution simulating the viscosity of blood (2.3 cP) with a hematocrit

of 40%. Each catheter was tested four times at each viscosity; twice with blood lines connected in standard configuration and twice with blood lines in reverse configuration. The simulated blood viscosity was created by diluting (1:4) a 38% glycerin-water solution to achieve a fluid viscosity of 2.3 cP. (Tab. II) (19). Fluid viscosity was verified using a viscometer (Brookfield DV-E, Middleboro, MA). Viscosity units are expressed in centipoise (cP); 1 centipoise = 1 milliPascal-second.

Catheter tip movement and the pattern of fluid flow at the catheter tip was documented by digital photography at three time points during the 30-second test; 1) fluid flow through the superior vena cava (2400 ml/min) but no flow through catheter, 2) initiation of simulated hemodialysis; at start of fluid flow (425 ml/min) through catheter and, 3) release of blue dye into the venous (outflow) lumen during simulated hemodialysis. A rapid sequence of 4-5 photographs was obtained at each time point. A total of 939 digital photographs were obtained during the 72 test procedures.

## Results

Subjective observations of catheter tip movement and fluid flow patterns are the primary results of this *in-vitro* investigation. Video imaging of fluid flow patterns of the different tip designs are available as supplementary material on the journal web site www.vascular-access.info. Fluid recirculation at the catheter tip, the objective measure of catheter performance, was visually evident during observation of the fluid flow patterns during the catheter testing procedures.

### *Catheter-tip movement*

*Step-tip catheters*

There was no movement of the distal tip of the Ultrastream™ catheter when blood lines were connected in standard or reverse configuration, or when the fluid viscosity was changed from 1.0 cP to 2.3 cP. There was no observable effect of the thin flow divider that horizontally splits the arterial end hole of the Ultrastream™ catheter.

There was no movement of the distal tip of the Titan™ catheter when the blood lines were connected in the standard configuration. However, upon activation of fluid flow (425 ml/min) there was a slight but noticeable wobble of the Titan™ catheter tip when the blood lines were reverse. This slight movement of the Titan™ catheter tip quickly stabilized and did not cause the distal tip to contact the glass column. When fluid viscosity was changed from 1.0 cP to 2.3 cP there was no change in the stability of the Titan™ catheter tip. At both viscosities there was a slight initial movement of the catheter tip but only when the blood lines were reverse.

There was slight movement of the ProGlide™ catheter tip with standard and reverse blood lines. Immediately upon activation of fluid flow there was an abrupt, slight deflection of the ProGlide™ tip but it did not touch the wall of the glass column. The degree of tip movement appeared similar when blood lines were connected in standard and reversed configurations, and when the fluid viscosity was changed from 1.0 cP to 2.3 cP.

*Split-tip catheters*

The Equistream™ and Centros® catheters have wide, transverse separation of the arterial and venous limbs along the distal tip. This wide separation causes at least one distal limb to contact the glass column before initiating any fluid flow. Catheter tip contact with the glass column stabilized movement of the Equistream™ and Centros® catheters during the testing protocols.

When the Equistream™ catheter was positioned within the mechanical model, before initiating fluid flow, the distal arterial limb contacted the glass column. Upon initiation of simulated hemodialysis the distal arterial limb remained in contact with the glass column with blood lines connected in standard and reverse configurations, and with fluid viscosity of water (1.0 cP) and simulated blood (2.3 cP). The distal arterial limb remained in contact with the glass column when simulated hemodialysis treatment was stopped.

When the blood lines were connected in standard configuration the distal tip of the Hemosplit® XK catheter remained centered and stable but the arterial and venous limbs moved closer together. When blood lines were reverse the venous limb moved against the wall of the glass column. Aspiration through the venous end hole caused adherence to the glass column. These movements of the Hemosplit® XK catheter tip did not change when the fluid viscosity was changed from 1.0 cP to 2.3 cP. Of note, when blood lines were reverse there was rapid accumulation of stagnant blood (blue dye) between the arterial and venous limbs of the Hemosplit® XK catheter.

The distal tip of the Centros® catheter is designed to have a wide stance within the superior vena cava. Before initiation of fluid flow the distal venous limb contacted the wall of the 24 mm-diameter glass column. Upon initiation hemodialysis (425 ml/min) the jet of fluid exiting the catheter tip increased the separation between the two curved limbs. This increased the pressure exerted by the venous limb against the glass column. The arterial limb of the Centros® catheter did not contact the glass column during simulated hemodialysis. The off-axis alignment of the arterial and venous end holes caused slight anterior-posterior movement of the Centros® catheter tip. These movements of the Centros® catheter tip were the same with standard and reverse blood lines. The change in fluid viscosity from 1.0 cP to 2.3 cP did not affect movement of the Centros® catheter tip.

The Ash Split® was the only catheter to exhibit significant tip movement when the blood lines were connected in standard configuration. Immediately upon activation of fluid flow (425 ml/min) the venous limb moved against the wall of the glass column. The venous limb remained in contact with the glass column until simulated hemodialysis flow was stopped. This movement of the venous limb was caused by the jet of fluid exiting the guidewire hole (1.25 mm × 2.75 mm) in the distal venous limb. When fluid viscosity was increased from 1.0 cP to 2.3 cP both the arterial and venous limbs moved against the glass column. When the blood lines were reversed both the arterial and venous limbs remained centered and stable in the simulated superior vena cava. However, when the blood lines were reversed there was accumulation of stagnant blood (blue dye) between the arterial and venous limbs of the Ash Split catheter. The Ash Split and Hemosplit®

XK catheters had accumulation of stagnant fluid between the split limbs when blood lines were connected in reversed configuration.

*Symmetric tip catheters*

The two symmetric tip catheters, the Palindrome™ and Symetrex catheters, remained centered and stable within the glass column with blood lines connected in standard and reverse configurations. The distal tips of both catheters remained stable when the fluid viscosity was changed from 1.0 cP to 2.3 cP. The Palindrome™ catheter tip has two 1.7 mm × 5 mm trapezoidal-shaped slots located 22 mm from the arterial and venous end holes. There was minimal movement of blue indicator dye through these side slots when blood lines were connected in standard or reverse configurations. The Symetrex catheter tip has two 8 mm × 2 mm horizontal slots that extend to the arterial and venous end holes.

***Catheter-tip recirculation***

All nine hemodialysis catheters had 0% recirculation when blood lines were connected in standard configuration. However, with reverse blood lines catheter tip design significantly affected the percentage of recirculating fluid (Tab. III).

*Step-tip catheters*

The Ultrastream™, Titan™, and ProGlide™ catheters are similar in design and have A/V offset lengths of 20 mm, 25 mm, and 30 mm, respectively. All three step-tip catheters had 0% recirculation when blood lines were connected in standard configuration. With reverse blood lines there was a jet of fluid from the arterial end hole that created a turbulent cloud of blue indicator dye around the distal tip of each step-tip catheter. The shape and location of this turbulent cloud was affected by different features of each catheter tip design. With blood lines connected in reverse configuration, and using water (1.0 cP) as the circulating fluid, the Ultrastream™, Titan™, and ProGlide™ catheters had recirculation rates of 15.8%, 20.5% and 17.3%, respectively. When fluid viscosity was changed to 2.3 cP (blood) the Ultrastream™, Titan™, and ProGlide™ catheters had recirculation rates of 8.7%, 9.4% and 16.3%, respectively.

The Ultrastream™ catheter had the lowest percentage of recirculating fluid at both fluid viscosities. The Ultrastream™ has a thin flow barrier which divides the horizontal midline of the arterial end hole. When blood lines are reversed this thin flow barrier may stabilize the jet of fluid exiting the arterial end hole. This stabilizing effect may minimize the percentage of recirculating fluid.

The Titan™ catheter has a low profile (1.0 mm) beveled ramp in front of the arterial end hole. When connected with reverse blood lines and using the viscosity of blood (2.3 cP), the Titan catheter had 9.4% recirculation. When connected with reverse blood lines and using the viscosity of water (1.0 cP), the Titan™ catheter recirculation was much higher (20.5%). This high recirculation was caused by the jet of fluid exiting the arterial end hole creating a turbulent flow pattern near the inflow (venous) end hole. When using a higher viscosity fluid (2.3 cP) during simulated hemodialysis treatment the turbulence was located downstream from the inflow end hole thereby minimizing the percentage of recirculated fluid.

The ProGlide™ catheter has a thick vertical flow barrier separating the arterial and venous end holes. When connected with reverse blood lines there is a jet of fluid exiting the arterial end hole which impacts the vertical flow barrier creating a cloud of turbulent fluid around the distal tip. When the ProGlide™ is connected with reverse blood lines, some of the turbulent fluid is aspirated into the venous end hole increasing recirculation 17%.

*Split-tip catheters*

All four split-tip catheters had 0% recirculation when the blood lines were connected in the standard configuration. The Equistream® catheter had 0% recirculation with blood lines connected in standard and reverse configuration, and with fluid viscosity of 1.0 cP and 2.3 cP. With the blood lines reverse and using water (1.0 cP) as the circulating fluid the Ash Split®, Hemosplit® XK and Centros® catheters had recirculation rates of 29.7%, 28.2% and 20.4%, respectively. With reverse blood lines and the viscosity of blood (2.3 cP) the Ash Split®, Hemosplit®, and Centros® catheters had higher recirculation rates of 39.2%, 33.5%, and 22.3%, respectively.

*Symmetric-tip catheters*

The two symmetric tip catheters, Palindrome™ and Symetrex, had 0% recirculation when the blood lines were connected in standard and reverse configuration, and when the fluid viscosity was 1.0 cP and 2.3 cP.

## Discussion

The purpose of this study was to observe the fluid flow patterns occurring at the distal tip of nine different tunneled hemodialysis catheters. The catheter testing system was a bench-top mechanical model that simulated conditions that occur during a routine hemodialysis treatment. The mechanical model worked well for evaluating different features of

**TABLE III -** Percent recirculation with reverse blood lines

| Viscosity | Centros® | Ash Split® | ProGlide™ | Ultrastream™ | Titan™ | Palindrome™ | Equistream® | Hemosplit® | Symetrex |
|---|---|---|---|---|---|---|---|---|---|
| 1.0 cP | 20.4 | 29.7 | 7.3 | 15.8 | 20.5 | 0.0 | 0.0 | 28.2 | 0.0 |
| 2.3 cP | 22.3 | 39.2 | 16.4 | 8.7 | 9.4 | 0.0 | 0.0 | 33.5 | 0.0 |

catheter tip design. The glass column provided clear observation of different fluid flow patterns that affected catheter tip movement and fluid recirculation. However, the mechanical model did not precisely replicate the physiologic conditions that occur at the distal tip of a hemodialysis catheter. The mechanical model did not simulate the hemodynamic effects of a functioning right atrium. Therefore, the observations and results of this *in vitro* study may be different than those obtained in a clinical environment.

***Validity of mechanical model***

During insertion of a tunneled hemodialysis catheter, the distal tip is often positioned in the upper right atrium when the patient is in a supine position. When the patient assumes an upright position the catheter will retract and the distal tip often moves into the superior vena cava. The mechanical model used in this study simulated the anatomic size, orientation, intravenous pressure, blood viscosity, and rate of blood flow in the superior vena cava. The catheter testing system attempted to replicate the physiologic conditions that occur at the catheter tip during a routine hemodialysis treatment.

The diameter and length of the superior vena cava is dependent upon age, gender, and body habitus (14). In a study of 32 hemodialysis patients with upper arm fistulas who underwent central venous computed tomography, the diameter of their superior vena cavae ranged from 12 mm to 29 mm (mean 21.1 mm) (15). In another study of 31 normal subjects who underwent magnetic resonance imaging (MRI) the diameter of their superior vena cavae ranged from 15 mm to 26 mm (mean 18.7 mm) and the length ranged from 41 mm to 70 mm (mean 53 mm) (14). The catheter testing system used a simulated superior vena cava measuring 24 mm in diameter and 350 mm in length, which represents a large superior vena cava. Catheter tip wall contact observed in this study would likely occur in patients with an average diameter (20 mm) superior vena cava.

The mechanical model pumped a fluid flow rate of 2400 ml/min through the simulated superior vena cava. The normal rate of blood flow through the superior vena cava is an elusive value (19). MRI and transthoracic ultrasonography studies report blood flow rates in centimeters per second; ranging from 7.2 cm/sec to 28.5 cm/sec (20, 21). In a study reported by Mareels et al, a computer model was created to measure catheter tip shear stress using blood velocity of 0.18 m/sec, which corresponded to a volume flow rate of 2700 ml/min (10). Other investigators evaluating temporary hemodialysis catheters used a simulated superior vena cava with a blood flow rate of 2000 ml/min and a diameter of 30 mm (22). Normal venous pressure in the superior vena cava, range from 3 mm Hg to 8 mm Hg (17, 18). The vertical orientation of the catheter tip created an intravenous pressure of 8 mm Hg within the glass observation chamber.

Chronic hemodialysis patients receiving appropriate iron therapy typically have hematocrit values ranging from 30% to 40% (23). The hemodialysis catheters were tested using fluid simulating the viscosity of blood with a hematocrit of 40% (24).

Glycerin, the circulating fluid in the mechanical model, does not precisely replicate the rheological behavior of blood flowing through the superior vena cava. Glycerin is a Newtonian fluid; its viscosity remains stable with changes in fluid velocity. Venous blood flow behaves as a non-Newtonian fluid; its viscosity decreases with increasing velocity of the bloodstream (12). During hemodialysis treatment, the blood pumped through a hemodialysis catheter has a higher velocity, and therefore lower viscosity, when compared to the viscosity of blood flowing through the patient's superior vena cava. This difference in fluid viscosity likely influences the degree of turbulence induced by different features of catheter tip design. This difference in fluid viscosity was not replicated in the mechanical model used in this study. To assess the effect of fluid viscosity on catheter tip behavior the study catheters were tested using the viscosity of water (1.0 cP) and the viscosity of blood (2.3 cP). This change in fluid viscosity affected only one catheter - the Ash Split® catheter. When connected with standard blood lines and using fluid viscosity of 1.0 cP, upon initiation of fluid flow through the Ash Split® the venous limb immediately moved against the wall of the glass column. When the fluid viscosity was increased to 2.3 cP both the arterial and venous limbs immediately moved against the glass column. The change in fluid viscosity from 1.0 cP to 2.3 cP during catheter testing caused a decrease in the percentage of recirculating fluid through the Ash Split®, Ultrastream™, and Titan™ catheters, and a slight increase in recirculation through the Hemosplit® XK catheter.

***Effects of hemodialysis catheter-tip design***

*Catheter tip movement*

The two symmetric-tip catheters, the Palindrome™ and Symetrex, remained stable and showed no tip movement when connected with standard or reverse blood lines, and with both fluid viscosities. The three step-tip catheters, the Ultrastream™, Titan™, and ProGlide™, are similar in design and exhibited similar catheter tip movements. The wide stance of the Centros® and Equistream® catheters caused at least one limb to contact the glass column (24 mm) before initiating fluid flow. The clinical significance of catheter-to-SVC wall contact is variable and not well understood.

The Ash Split® catheter exhibited tip movement as a result of catheter tip design. When the Ash Split® is connected with standard blood lines there is a jet of fluid exiting the guidewire hole in the distal venous limb which forces the catheter tip against the wall of the glass column. The distal tip of the venous limb has a tapered internal diameter which partially obstructs fluid flow thereby increasing intraluminal pressure which produces the jet of fluid exiting the guidewire hole. There is no guidewire hole in the distal tip of the arterial limb so when connected with reverse blood lines the distal tip of the Ash Split® remained centered and stable within the simulated superior vena cava.

*Catheter-tip recirculation*

The percentage of recirculating fluid directly affects the efficiency of hemodialysis treatment (14). Previously published

clinical studies of hemodialysis catheter performance have reported recirculation rates that are lower and higher than those measured using our mechanical model (8, 25-27). Pannu et al reviewed the clinical performance of 102 hemodialysis catheters and reported findings that are similar to our own; recirculation (>10%) was infrequent (3%) when blood lines were connected in standard configuration, but much higher (86%) when blood lines are reversed (25).

The percentage of recirculating fluid is an objective measure of catheter tip design. All nine hemodialysis catheters evaluated in this study had 0% recirculation with standard blood lines and catheter blood flow rate of 425 ml/min. When blood lines were reversed, the different features of catheter tip design affected the percentage of recirculating fluid. With reverse blood lines the split-tip catheters had higher recirculation (20% to 35%) when compared to step-tip catheters (9% to 16%) and symmetric tip catheters (0%). With reverse blood lines and the viscosity of blood (2.3 cP) the three step-tip catheters had clinically significant recirculation due to a jet of fluid exiting the arterial end hole flowing towards the venous end hole; the effluent mixes with the influent. The Ultrastream™, Titan™, and ProGlide™ catheters have two small side holes positioned 3.0 mm, 2.5 mm and 5.0 mm, respectively, from the venous end hole. The pattern of recirculation rates (9%, 9%, 16%) with reverse blood lines suggests that the location of the two side holes can influence fluid recirculation. The Ultrastream™ catheter has a thin, horizontal flow barrier extending from the midline of the arterial end hole to the venous end hole, parallel to the direction of blood flow. This flow barrier did not disrupt fluid flow from the arterial end hole to the venous end hole, recirculation, with reverse blood lines. Similarly, the Titan™ catheter has a V-shaped, low profile, beveled flow barrier that did not affect the fluid flow pattern at the distal tip when connected with reverse blood lines. The thick vertical flow barrier on the tip of the ProGlide™ catheter did disrupt the jet of fluid exiting the arterial end hole. This created a cloud of effluent fluid that was aspirated into the venous end hole when the ProGlide™ was connected with reverse blood lines.

All four split-tip catheters had no fluid recirculation when connected with standard blood lines. When tested with reverse blood lines and viscosity of blood (2.3 cP) the Ash Split®, Hemosplit® XK, and Centros® catheters had recirculation rates of 39.2%, 33.5%, and 22.3%, respectively. These high rates of recirculation are due to the fluid jet exiting the arterial end hole flowing towards the venous end hole. The Centros® catheter has the shortest A/V offset, the shortest split length, and lowest recirculation when compared to the Asp Split® and Hemosplit® XK catheters. The presence of side holes in the distal tip of the Ash Split® and Hemosplit® XK catheters increased the percentage of recirculation with reverse blood lines.

In summary, distal tip design can influence the performance of a tunneled hemodialysis catheter. Eight of the nine tested catheters performed well when blood lines were connected with standard blood lines. With reverse blood lines, symmetric tip and step-tip designs had stable fluid flow patterns, less tip movement and lower recirculation rates when compared to split-tip designs.

## Disclosures

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Conflict of interest: Dr. Vesely is a consultant for Phase One Medical. Adrian Ravenscroft is Chief Executive Officer at Phase One Medical.

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