Comparison of Symmetric Hemodialysis Catheters Using Computational Fluid Dynamics

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ABSTRACT

Purpose: Symmetric-tip dialysis catheters have become alternative devices because of low access recirculation and ease of tip positioning. Flow characteristics of three symmetric catheters were compared based on computational fluid dynamics (CFD) as they relate to catheter function.

Materials And Methods: In Palindrome, GlidePath, and VectorFlow catheters, a computational fluid dynamics–based approach was used to assess (i) regions of flow separation, which are prone to thrombus development; (ii) shear-induced platelet activation potency; (iii) recirculation; and (iv) venous outflow deflection. A steady-state, laminar flow model simulated catheter tip position within the superior vena cava. Catheter performance was investigated at high hemodialysis flow rate (400 mL/min). Blood was assumed as a Newtonian fluid.

Results: Wide regions of flow separation downstream of the Palindrome side slot and close to the distal tip were observed in forward and reversed line configurations. Geometric asymmetry of the distal guide wire aperture of the GlidePath catheter produced the highest levels of inverted velocity flow when run in reversed configuration. The lowest mean shear-induced platelet activation was exhibited by GlidePath and VectorFlow catheters; the Palindrome catheter exhibited 152% higher overall platelet activation potency. All catheters were associated with a recirculation close to zero; the helically contoured lumens of the VectorFlow catheter produced the greatest amount of deflection of venous flow away from the arterial lumen.

Conclusions: The VectorFlow catheter produced less shear-induced platelet activation than the Palindrome catheter and less flow separation than the Palindrome and GlidePath catheters irrespective of line configuration. These findings have potential implications for differences in thrombogenic risk during clinical performance of these catheters.

ABBREVIATIONS

CFD = computational fluid dynamics, PAS = platelet activation state, SVC = superior vena cava, 3D = three-dimensional

More than 400,000 Americans receive renal replacement therapy through hemodialysis. Despite native fistula placement being the preferred form of permanent access, catheters remain the initial access for the majority of patients in the United States, and they serve as a "bridge" to new access creation in patients with failed arteriovenous access (1).

Catheter thrombosis and infection remain causes of vascular access–related morbidity (2). Catheter performance during dialysis is also a challenge, as the use of catheters with higher recirculation and/or reduced clearance will result in inadequate dialysis sessions (3). Inadequate dialysis has been shown to be an independent predictor of increased hospitalizations, hospital days, and Medicare inpatient expenditures among patients receiving hemodialysis (4).

Differences in catheter tip design can produce significant differences in flow characteristics during the high-flow conditions required during dialysis, and in turn can have important implications for catheter thrombogenicity, recirculation, and other critical parameters of catheter performance (5). Symmetric-tip catheters have become alternatives to conventional step-tip and split-tip catheters,

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Appendix E1, Figure E1, and Videos E1-E6 are available online at *www.jvir.org*.

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in part because of the ability to reverse lines during dialysis without an increase in recirculation (6). These differences were assessed among three commercially available symmetrical tip catheters with the use of computational fluid dynamics (CFD), as widely applied to study the hemodynamic performance of catheters (7–9).

MATERIALS AND METHODS

Computational Fluid Dynamics

CFD simulations were designed to investigate and compare local hemodynamics in three commercially available symmetric-tip dialysis catheters: Palindrome (Covidien, Dublin, Ireland), GlidePath (Bard Access Systems, Salt Lake City, Utah), and VectorFlow (Teleflex, Wayne, Pennsylvania). High-resolution computer-aided design models of each catheter (**Fig 1**) were created as follows: the Palindrome catheter was measured with a touch probe coordinate machine, and the resultant measurements were used to generate a high-resolution three-dimensional (3D) model in SolidWorks (Dassault Systems, Vélizy-Villacoublay, France). For the GlidePath catheter, internal and external surfaces were scanned within a high-resolution industrial computed tomography system (GKS Services, Minneapolis, Minnesota), and the resulting 3D dataset was then rendered into SolidWorks. Both techniques ensured high accuracy in the reconstruction of every geometric characteristic of the catheter models. The VectorFlow catheter was rendered by using design-control SolidWorks files. The 3D models were coaxially placed inside a cylindrical conduit (as detailed later) ideally resembling the SVC and processed to build discrete grids (in which the governing equations of fluid motion have to be numerically solved) by using the general-purpose solid modeler ICEM (ANSYS, Canonsburg, Pennsylvania). The computational grid consisted of more than 8 million discrete tetrahedral/hexahedral cells (0.2-mm average edge size).

Model Assumptions

A previously validated CFD model (9) was used to simulate catheter tip position within the SVC, as it is currently not feasible to simulate hemodialysis catheters within a robust right atrial model because of the complexity of assumptions regarding atrial anatomy, proportion of flow from the inferior vena cava, and tricuspid valvular function. The SVC flow conditions were realistically assumed as 3 L/min within an 18-mm-diameter, 480-mm-long conduit with standard assumptions of adult human blood (uncompressible Newtonian fluid model [10] with viscosity μ 3.5 mPa $\cdot$ s and density ρ 1,060 kg/m^3). Catheter performance was evaluated at a 400 mL/min flow rate, in accordance with optimal clinical practice, with the catheters run in forward and reversed line configurations. A detailed description of the methodology applied to prescribe the conditions at boundaries is available in **Appendix E1** (available online at *www.jvir.org*).

CFD Simulations and Postprocessing

For all models, flow fields were computed by solving the 3D, steady-state (assumption based on the low pulsatility characterizing venous flow) governing equations of fluid motion in discrete form by using a finite volume-based commercial code (Fluent; ANSYS). Each catheter was initially studied by using classical fluid-dynamic theoretical analysis, which verified the soundness of the assumption of flow laminarity. Sensitivity analysis was carried out to assure grid-independence of the solution. Each catheter was run in forward and reversed directions to simulate clinical practice. A detailed description of the computational settings is provided in **Appendix E1**.

Analysis of Thrombogenic Flow Patterns Inside Catheters

The thrombogenic potency of the geometric features of the catheters was evaluated in terms of position and

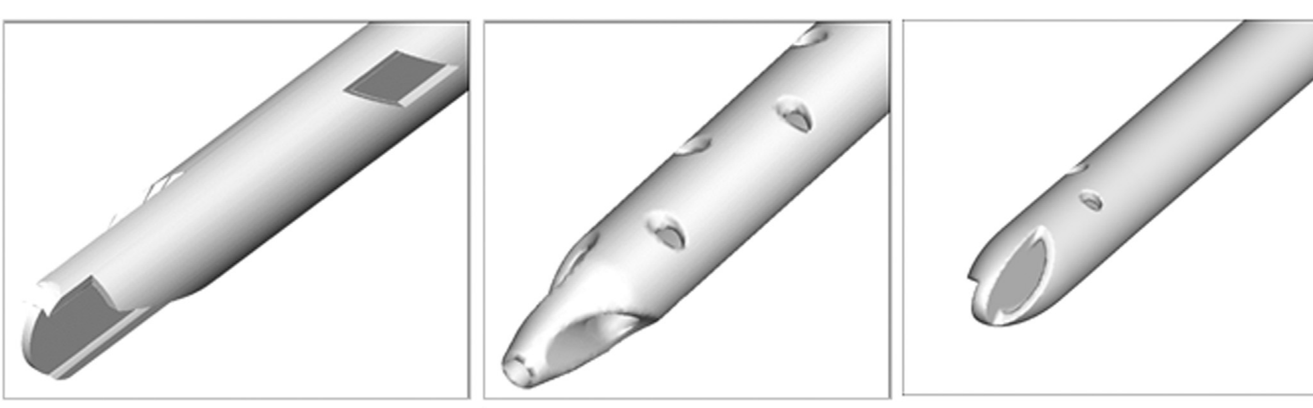

Figure 1. Three-dimensional computer-aided design models of the Palindrome **(a)**, GlidePath **(b)**, and VectorFlow **(c)** catheters before tetrahedral/hexahedral meshing for analysis using CFD. The Palindrome catheter is completely symmetric. The GlidePath catheter is not perfectly symmetric; it has a guide wire aperture at the distal tip as part of the venous lumen, as well as offset side holes. The VectorFlow catheter has complete symmetry of its distal tip but offsetting of its side holes.