SIEMENS
Ingenuity for life

3-D CFD Optimization of a Hemodialysis Catheter

Aaron Godfrey, Thomas McIlwain, Patrick McGah, Kristian Debus
Siemens Industry Software

Introduction and Motivation

The U.S. reports more than 400,000 patients receiving dialysis treatment for end stage renal failure. Catheters serve as the primary means of providing dialysis treatments to new patients as well as on a sustained basis for those who have arteriovenous damage severe enough to prevent the use of a permanent access fistula. Catheter use is, however, not without risk. They are known to be susceptible to both thrombosis – the formation of a blood clot, and hemolysis – the rupturing of red blood cells releasing their contents into the bloodstream. Both of these contribute to the occurrence of vascular access morbidity. As many as 25% of catheters can result in at least a partial thrombosis.

In addition, catheters must be shown to operate with a minimum of blood recirculation – newly dialyzed blood being returned to the dialysis machine prior to circulating through the body. The current study uses 3-D CFD simulations to evaluate catheter performance in all three of these areas. An optimization algorithm is used to find new design concepts which will reduce the occurrence of thrombosis, hemolysis, and recirculation for the many patients dependent on catheters for their lives.

Materials and Methods

A parametric CAD model was developed in the Simcenter STAR-CCM+ multiphysics simulation package. It was generic in nature and does not represent any commercial catheter known to the authors, but does include many of the basic design elements common in catheters today. Eighteen geometric parameters allow for a wide variety of designs. STAR-CCM+ was used to automate the CAD, meshing, and CFD solution processes.

Figure 1

Figure 1. Baseline catheter model. The parametric CAD model allows for independent control of arterial and venous lumens with regard to hole number, size, aspect ratio, cut angle, position, and spacing. It also allows for complete control of the tip cut angle.

The CFD model comprises the catheter geometry inside an idealized section of the superior vena cava (modeled as a cylinder of diameter 18 mm). The flow in this section of the vascular system can be approximated as laminar with constant boundary conditions. The material properties of blood were taken to be a density of 1060 kg/m^3 and a viscosity of 3.5 mPa·s. Flow through the superior vena cava and catheter were set to 3 l/min and 400 ml/min respectively.

Though thrombosis is a result of the complex and poorly understood blood clotting cascade, the contribution from the hemodynamic environment is better understood. Thrombosis performance was characterized as the volume percentage of separated or reversed flow in the model as these have been shown to strongly predict the incidence of catheter-induced thrombosis.

An Eulerian model of hemolysis was implemented based on the work of Garon, A. which simulates the modified index of hemolysis (MIH) for each design.

Recirculation was monitored via a passive numerical tracer.

A hybrid-adaptive optimization algorithm SHERPA was used to solve a multi-objective optimization problem to minimize separated flow and MIH subject to the constraint that blood recirculation must be less than 0.05% by volume. The optimization was allowed to investigate 500 designs over the course of a 10 day period using 128 cores on a Linux high performance computing cluster.

Figure 2

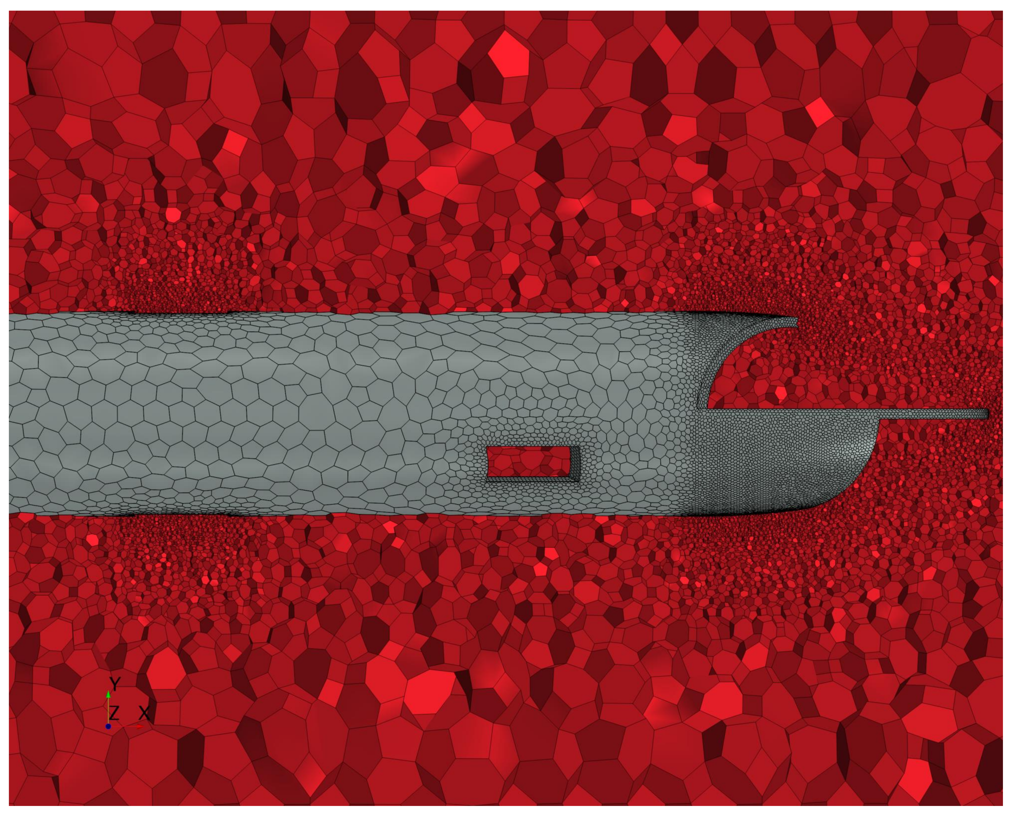

Figure 2. Cut section of computation mesh for baseline catheter model. No prism layers are included due to the fact that the solution was laminar. The number of cells was somewhat dependent on the parameter values of a specific design but fell within the range of 200k to 500k cells.

Results and Discussion

The generic baseline simulation was shown to have thrombosis, hemolysis, and recirculation values that were generally in line with those reported for modern commercially available catheters. The best designs found over the course of the study showed separation values that were reduced by as much as 67% and hemolysis values that were as much as 48% relative to those baseline values. Inspection of the results identified two basic design concepts. These clusters of designs can be seen in Figure 3 below. The first group labelled "Better" retains nearly all the characteristics of the baseline with minor variations that appear to tune performance. The second group labelled "Best" was a set of unique designs which were quite different from the baseline. They were predicted to have the most improvement in both objectives.

Figure 3

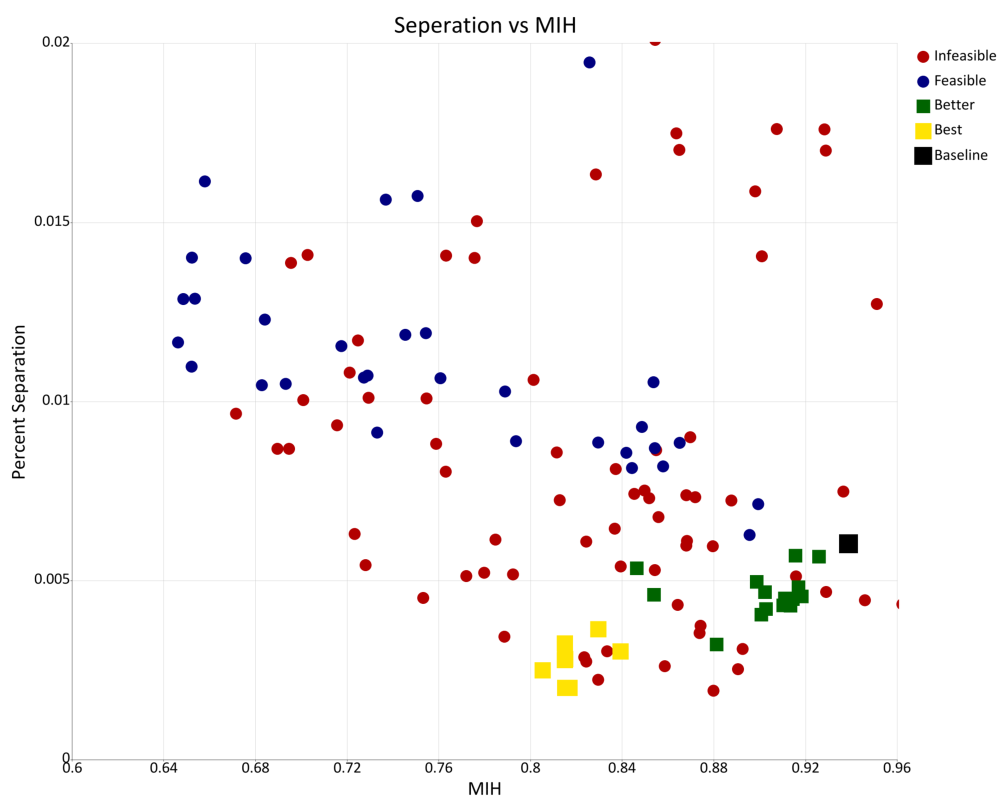

Figure 3. Plot of separation (proxy for thrombosis) against MIH. The plot has been zoomed in to show the most interesting designs. The blue and green squares highlight the two principle design concepts which were found to have improved both the objectives. Feasible and infeasible indicate whether or not a given design satisfied the recirculation constraint.

The generic baseline simulation was shown to have thrombosis, hemolysis, and recirculation values that were generally in line with those reported for modern commercially available catheters. The best designs found over the course of the study showed separation values that were reduced by as much as 67% and hemolysis values that were as much as 48% relative to those baseline values. Inspection of the results identified two basic design concepts. These clusters of designs can be seen in Figure 3 below. The first group labelled "Better" retains nearly all the characteristics of the baseline with minor variations that appear to tune performance. The second group labelled "Best" was a set of unique designs which were quite different from the baseline. They were predicted to have the most improvement in both objectives.

Figure 4

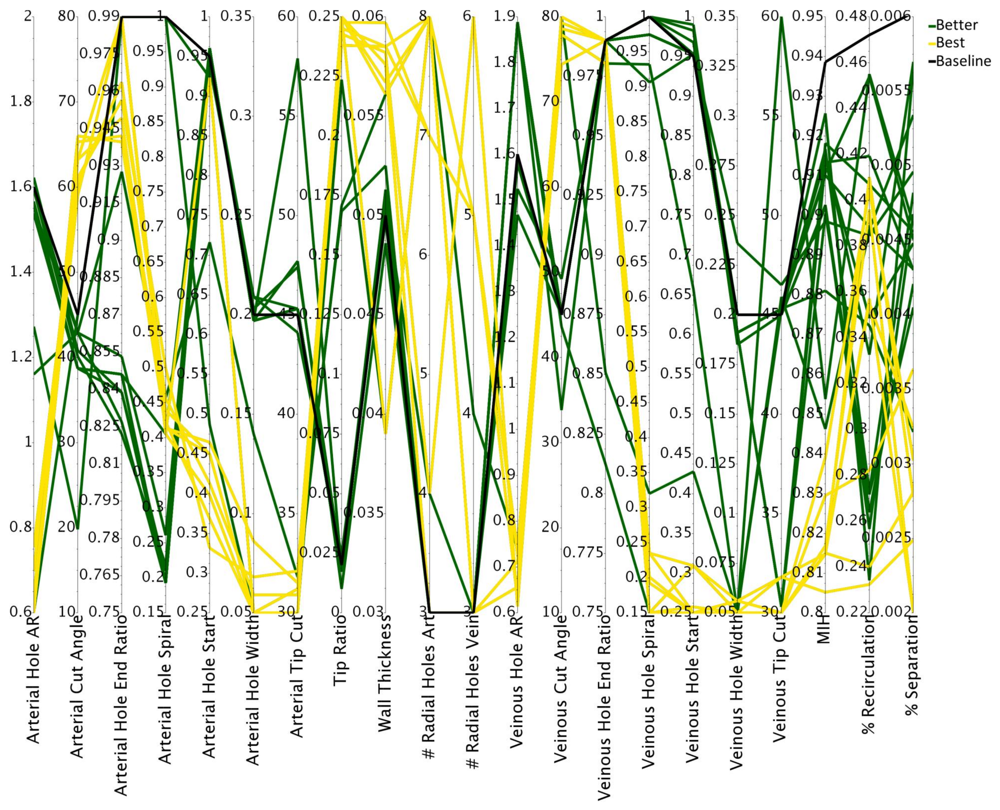

Figure 4. Parallel coordinate plot of the baseline and best and better design groups. This highlights the relative similarity between the better design group and the baseline design as well as the significant differences found in the best designs.

Figure 5

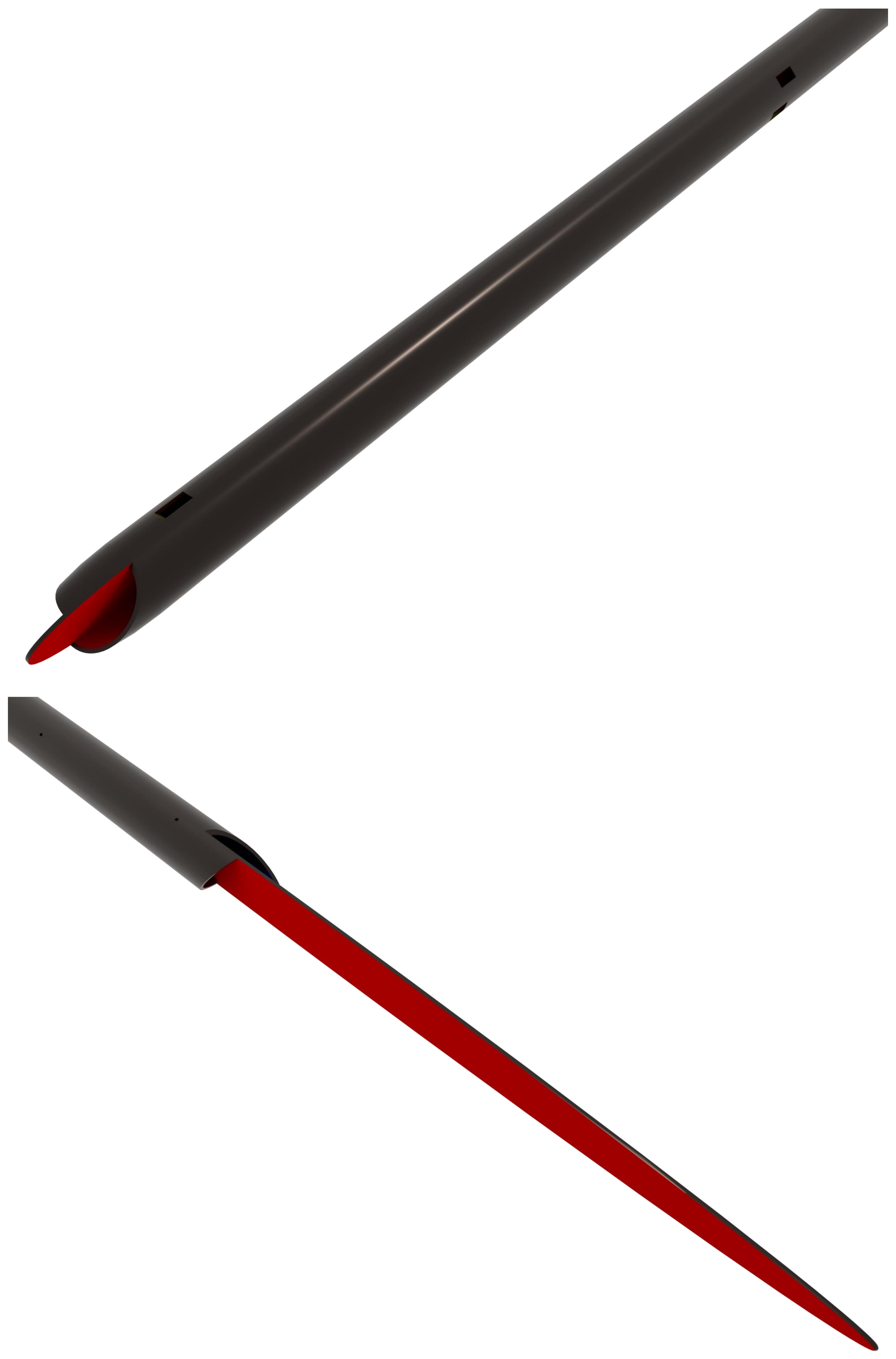

Figure 4. Representative designs for "Better" (upper) and "Best" (lower) design groups.

Conclusions and Future Work

The current work demonstrates the feasibility of CFD based optimization for hemodialysis catheters as well as identifying some novel design concepts with the potential to reduce the risk of thrombosis and hemolysis.

References

Garon, A., Artificial Organs 2004, 11(28), 1016-1025
Clark, T., J Vasc Interv Radiol 2015, 26:252-259