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Structural Mechanics of Cooling Catheters

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Abstract:
This paper describes the use of structural mechanics capabilities within Comsol to explore new cooling catheter designs. Cooling catheters may be used to save ischemic tissue resulting from strokes or heart attacks. Cooling catheters we are developing circulate both blood and coolant internally. Typical guide catheters use metallic braiding to ensure torsional strength. Braiding, however, displaces space for flows and limits design options. To explore alternatives to braiding, the work described in this paper was started. Beginning with geometry and material property requirements both homogeneous and composite tube models were explored. Comsol successfully predicted angle of twist along the longitudinal length of catheter for both models. Various plastic composite tubes were modeled, none reaching the equivalent torsional strength to braided catheters. Future work will extend these initial models to find alternatives to standard braided tube configurations.

Keywords: catheter, torsion, composite, structural, and mechanics.

1. Introduction

A growing body of medical research suggests that inducing mild to moderate hypothermia (2-3 degrees Celsius temperature drop) in the brain or heart following blood flow interruption can reduce organ damage[1]. Therapeutic hypothermia is most effective when applied quickly after organ trauma and selectively to the vulnerable tissue[2]. We have demonstrated that selective organ cooling is possible with the use of percutaneously inserted catheters.

Our cooling catheters have multiple lumens, or channels, through which different fluids can flow as shown in Figure 1[3]. Multiple lumens are used to deliver both blood, lumen 3, and closed circuit cooling, lumens 1 and 2 (Fig.1). Most percutaneously inserted guide catheters are inserted through the patient's groin and are threaded through the femoral artery to the target organ. These catheters "guide" balloon catheters to the correct location in the body. This delivery approach dictates the dimensions of the catheters and their design. The catheters are typically 2-4 millimeters in outer diameter, 1-1.5 meters in length. Testing has shown that catheter insertion can require torques of up to 0.003 N-m. This torque is a result of the force applied to overcome the frictional resistance between the catheter and the vasculature. To accommodate high length to width ratios (~ 400 to 1) and ensure proper catheter mechanical behavior, most guide catheters are composed of multiple layers of polymers with an embedded stainless steel lattice as shown in Figures 2 and 3[4]

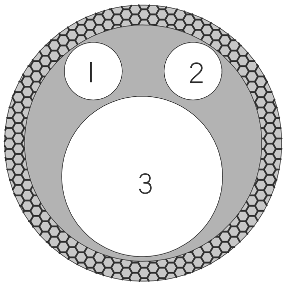

Figure 1: Cross section of a multiple lumen catheter

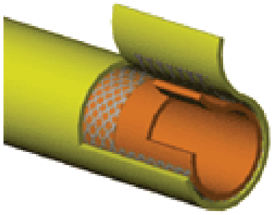

Figure 2: Cross section of a single lumen catheter, showing metallic braid and plastic layers.

While braided composites are widely used for catheter design, braiding is problematic for our cooling catheters. The braiding consumes space within the catheter cross section, reducing available space for coolant circulation and blood flow. As a result, potential blood flow rates are diminished and required coolant pumping pressures are increased.

Catheter design is a complex exercise in balancing competing material properties. The distal tip of the catheter, which is advanced through the vasculature, must have high flexibility to avoid vasculature trauma. In contrast, the proximal end, which is manipulated by the doctor, must be rigid to withstand torque and axial loading without buckling. This requires that the construction of the catheter vary with respect to its length[5]. Making the catheter flexible or rigid based on its length is typically accomplished by changing the angle of the steel braid or by reducing the diameter at the distal tip. An example of a tip reduction can be seen in Figure 3.

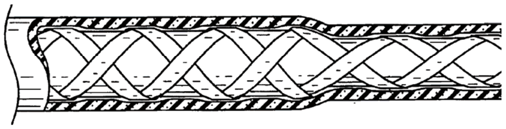

Figure 3: Cut away profile of a typical catheter

The incorporation of steel bands at various angles of inclination coupled with multiple lumens and laminated layers of polymers makes the analytical analysis of catheters complex. Cooling catheters also change mechanical properties when one or more lumens are filled with pressurized coolant and or blood, further increasing the complexity of the analysis. In this study these effects were neglected.

This paper presents a foundational study to understand the mechanics of our cooling catheters. We had two goals. First we set out to compare COMSOL predictions to analytical solutions for a homogeneous tube and then a composite tube using standard medical plastics. Second, with COMSOL solutions verified, we explored the mechanics of other composites that might allow the removal of braiding. Results, however, showed that braiding is likely a "must have" for needed torsion characteristics.

2. Catheter Design Equations

Besides obvious geometry characteristics, catheter designers also consider: "pushability", "torqueability", and flexibility. Pushabilty refers to the catheters response to longitudinal forces. Torqueability refers to the catheter's response to applied torques about its longitudinal axis. Flexibility refers to the catheter's response to bending moments applied along its longitudinal axis. This study focuses on torqueability.

To ensure that adequate blood flow and coolant flow inside a cooling catheter, the catheter must not twist upon itself or in other words kink during insertion. The **equation for the twist angle, ϕ,** for a tube under pure torsion is:

$$\phi = \frac{TL}{GJ}$$

where T is the applied torque or moment, L is the length of the catheter, G is the shear modulus, and J is the polar moment of inertia. To minimize the amount of twist along our catheter we have limited options, since the applied torque is relatively fixed given the procedural needs, and the length as well is relatively fixed as a result of the procedure and anatomical geometry. As a result, the shear modulus and the polar moment of inertia are the primary design variables open to design change.

To express this conclusion in a compact mathematical form, catheter designers define **torsional stiffness** as:

$$k_{torq} = \frac{GJ}{L}$$

Roth notes that typical braided catheters with wall thicknesses of 0.1 mm, and an outer diameter of 1.0 mm have a k_{torq} ~ 1.46 kPa while a typical plastics like Pebax have a k_{torq} ~ 0.025 kPa.[5]

3. Use of COMSOL Multiphysics

COMSOL Multiphysics 3.4 with the MEMs module was used to perform finite element analysis on a number of tube configurations. These models were created by importing the desired tube geometries, drafted in SolidWorks, into COMSOL. The structural mechanics solid stress/strain mode was employed using the steady state solver. The conditions of pure torsion were created in COMSOL by fixing one end of the tube, and applying a tangential force couple to the opposite end of the tube. The application of the moment couple is illustrated in Figure 4, where the applied moment is (2*F)*R.

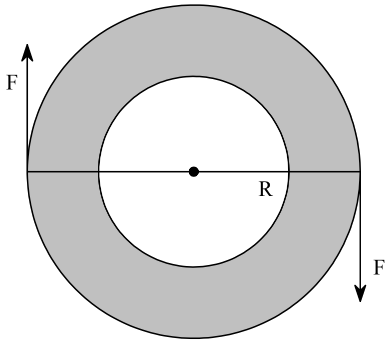

Figure 4: Force couple applied in COMSOL

Once the geometry, boundary conditions and loading cases had been established, the geometry was meshed into finite elements using the default COMSOL mesh parameters. After initial solutions were obtained, the mesh was further refined to decrease the mesh element size (Typical mesh statistics: 28,000 elements and 136,000 degrees of freedom). After the model was solved, COMSOL computed the deformed shape of each element in the model. Post processing was required to obtain the angle of twist. Calculation of the angle of twist used equation 1 inserted first into scalar expressions and then into the expression field of the post processing boundary window . A diagram of the cross-section is shown in Figure 5.

$$\phi = 2\sin^{-1}\left(\frac{\sqrt{u^2+v^2}}{\sqrt{X^2+Y^2}}\right), \qquad (1)$$

where: u is the displacement in the x direction
v is the displacement in the y direction
X is the initial x coordinate of the point
Y is the initial y coordinate of the point

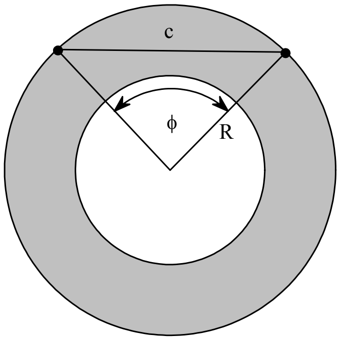

Figure 5: COMSOL calculation of ϕ diagram

4. Results

We demonstrated that COMSOL can accurately predict the angle of twist for both a homogenous tube and a composite tube. To reduce computational complexity both tubes were 5 cm in length. The homogenous tube consisted of Pebax 72D with outer diameter of 2.0 mm and a wall thickness of 0.5 mm. The composite tube was made of outer layer of Polyimide and inner layer of Pebax 72D. The inner and outer tubes had outside diameters of 1.5 mm and 2.0 mm, respectively. Both tubes had wall thicknesses of 0.25 mm. Pebax 72D and Polyimide have shear moduli of 434 MPa and 3450 MPa, respectively.

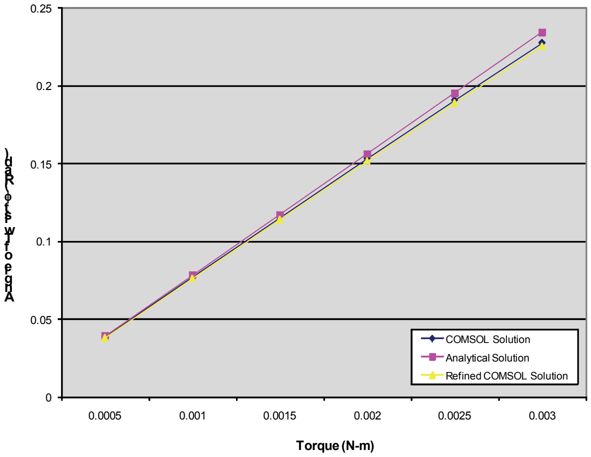

Figure 7: Homogenous tube results

The COMSOL solution for every data point agreed within 4% with the analytical solutions calculated prior to the computer simulations.

Results of this analysis are shown in Figures 7 and 8. The angle of twist shown reflects the value of ϕ at the point of applied torque for each case.

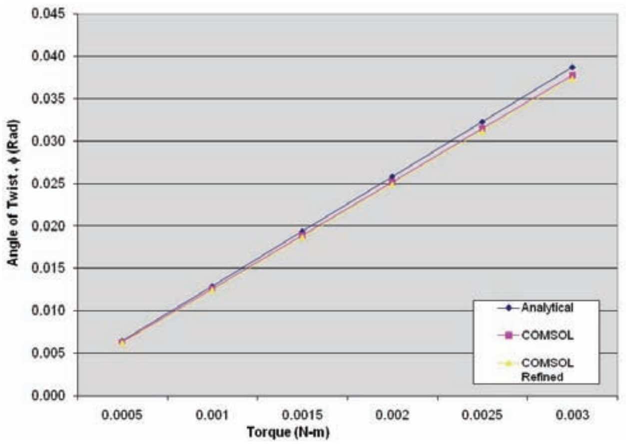

Figure 8: Simple composite tube results

Figure 6 shows values of ϕ along the longitudinal axis of a typical model. For this model the maximum value of phi was approximately 0.04 radians, with an applied torque of 0.003 N-m.

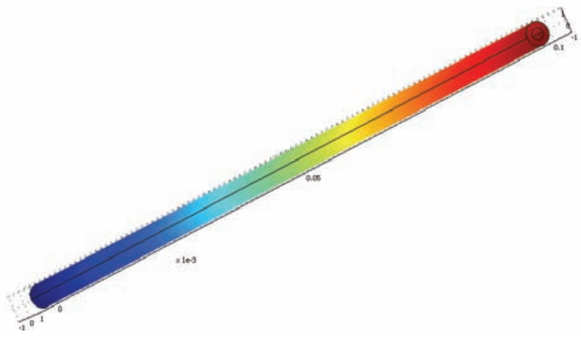

Figure 6: Sample COMSOL solution showing angle of twist variation along the longitudinal axis. Blue to the left is the minimum value and red to the right is the maximum value.

Having verified COMSOL's ability to predict the angle of twist of both homogeneous and composite tubes, the composite model was used to explore other composite designs that might have similar torsional properties as braided composites. Many combinations of common medical polymers were tested. The torsional stiffness of each was calculated and compared to typical values for braided composites. None of the polymer combinations tested achieved a torsional stiffness on the same order of magnitude as a braided composite.

5. Conclusion

We conclude that while the use of braiding in catheters has coolant and blood circulation drawbacks, braiding is likely necessary to achieve the mechanical properties required during catheter insertion. COMSOL enabled us to explore many different catheter designs quickly, with minimal expense. It will also enable us to explore alternatives to existing braided tube configurations.

6. References

References:

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7. Acknowledgements

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