# Modeling Blood Flow in a Tilted Inferior Vena Cava Filter: Does Tilt Adversely Affect Hemodynamics?

Michael A. Singer, PhD, and Stephen L. Wang, MD


## ABSTRACT

**Purpose:** Filter tilt is often seen with conical filters and adversely affects retrievability and clot trapping efficiency. In addition, tilt may also alter flow dynamics. This study uses computational fluid dynamics to evaluate flow past an unoccluded and partially occluded Celect inferior vena cava filter (Cook, Bloomington, Indiana). In particular, the hemodynamic response to thrombus volume and filter tilt is examined, and the results are compared with flow conditions known to be thrombogenic.

**Materials and Methods:** Computer models of an upright and tilted Celect filter are constructed using high-resolution digital photographs and methods of computer-aided design. The three-dimensional models are placed inside a model cava, and steady-state flow past unoccluded and partially occluded filters is computed.

**Results:** The volume of stagnant and recirculating flow increases with thrombus volume. In addition, as filter tilt increases, the cava wall in the direction of filter tilt is subjected to low-velocity flow and gives rise to regions of low wall shear stress.

**Conclusions:** Flow conditions caused by the tilted Celect filter may elevate the risk of intra/perifilter thrombosis and facilitate vascular remodeling. This latter condition may increase the potential for incorporation of the hook of the filter into the vena cava wall, thereby complicating filter retrieval. These findings also suggest that further long-term clinical follow-up with conical filters should be pursued with a specific evaluation of tilt as a factor of intrafilter thrombus and thrombosis.


## ABBREVIATIONS

DVT = deep vein thrombosis, IVC = inferior vena cava, NS = Navier-Stokes, PE = pulmonary embolism

Inferior vena cava (IVC) filters are a routine clinical treatment for the prevention of pulmonary embolism (PE) from deep vein thrombosis (DVT). An ideal IVC filter causes minimal disruption to the flow, effectively traps potential pulmonary emboli, is not inherently thrombogenic, is deployed through a low-profile delivery system, and exhibits no long-term clinical complications. The Prevention du Risque d'Embolie Pulmonaire par Interruption Cave (PREPIC) study group's 8-year follow-up of IVC filters versus anticoagulation alone found a decreased incidence of symptomatic PE in the filter group but also noted a statistically significant increase in the incidence of DVT with the filter group (35.7% vs 27.5%; $P$ = .042) (1). These results have spawned interest in using retrievable IVC filters to prevent PE, particularly with prophylactic placement in patients with relatively short-term risks for PE (eg, trauma and surgical patients).

With conical, retrievable filters, including the G2 (Bard Peripheral Vascular, Tempe, Arizona), the Celect (Cook, Bloomington, Indiana), and the Gunther Tulip (Cook), filter tilt is a common occurrence, and often problems occur when trying to retrieve the device (2–6). Retrieval of a tilted filter can be complicated by technically difficult engagement of the tip/hook with a snare because of position or angle as well as a tip that is embedded into the cava wall.

The Celect filter is the second generation of the Gunther Tulip IVC filter. Built using a similar conical design, the Celect has four hooked primary legs and eight shorter, curved secondary legs. The secondary legs are designed to decrease the frequency and severity of tilt in comparison with the first-generation Tulip filter. Recent studies on the Celect indicate the filter tilts greater than 5° in approximately 33% of cases (7), and severe tilt (> 15°–20°) occurs in approximately 3%–9% of cases (7–9).

With these relatively high rates of tilt, it is important to realize that clinical studies demonstrate attempted retrieval in only 26%–50% of retrievable filters deployed; therefore,

From the Center for Applied Scientific Computing (M.A.S), Lawrence Livermore National Laboratory, Livermore, California; and Division of Vascular and Interventional Radiology (S.L.W.), Kaiser Permanente Santa Clara, 700 Lawrence Expressway, Santa Clara, CA 95051. Received February 17, 2010; final revision received September 12, 2010; accepted September 23, 2010. **Address correspondence to** S.L.W.; E-mail: stephen.wang@alumni.duke.edu

Neither of the authors has identified a conflict of interest.



*J Vasc Interv Radiol 2011; 22:229–235*

DOI: 10.1016/j.jvir.2010.09.032

the majority of retrievable filters are left in place as permanent filters (2–3,10). Although the focus of recent studies on tilted filters has concentrated on tilt as a factor that complicates retrieval, this study aims to determine the impact of tilt on the hemodynamics inside the vena cava. In particular, if a large fraction of tilted filters becomes permanent filters, does tilt affect the risk of thrombosis? Does a tilted filter lead to hemodynamic conditions that may promote thrombosis, including areas of stagnant or recirculating flow or abnormal wall shear stress profiles?

Computational flow modeling has been used to study flow past IVC filters (11–13). However, all of these studies have evaluated filters in an ideal, centered position. In this study, we use computational fluid dynamics to evaluate the hemodynamics of an unoccluded and partially occluded Celect filter in nontilted and tilted positions with particular interest in identifying regions of flow that elevate the risk of thrombogenesis.

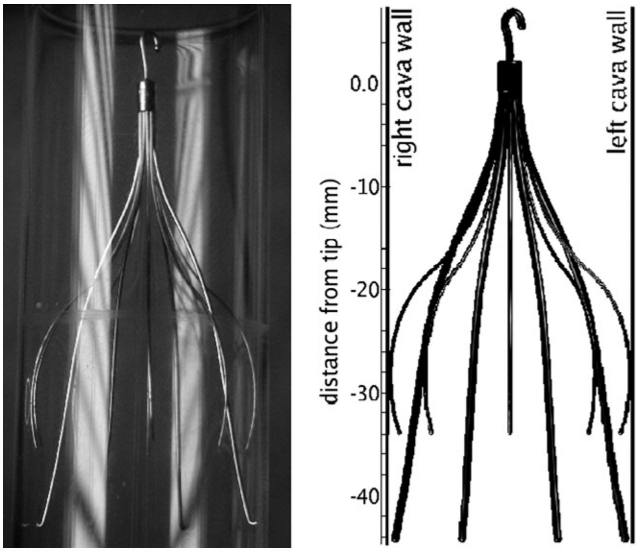

**Figure 1.** Celect filter. **(a)** Real filter in a glass test tube with a 23-mm inner diameter. **(b)** Three-dimensional computer model sized to fit the same tube.

## MATERIALS AND METHODS

The Celect IVC filter (**Fig 1**) is a low-profile, retrievable, nitinol filter that has been retrieved from patients after being implanted for more than 1 year (14). Patients whose risk of pulmonary embolism decreases with time may be candidates for retrievable filters such as the Celect. **Fig 1a** shows the real filter deployed in a glass test tube with an inner diameter of 23 mm; **Fig 1b** is the corresponding computer model.

The hook attached to the top of the filter allows retrieval of the Celect via a sheath inserted into the jugular vein. Fastening hooks at the end of the four straight legs (**Fig 1a**) attach to the IVC and hold the filter in place. The remaining eight curved legs are designed to support the filter and keep it centered in the vessel.

### Computational Models

The IVC is modeled as a straight, rigid tube with an inner diameter of 23 mm, per the average cava diameter described in Kaufman et al (15). The length of the tube is 104 mm, which provides adequate distance for the inlet velocity profile to develop fully before reaching the filter. Two overlapping grids are used to discretize the interior of the IVC: one high-resolution grid covers the inner boundary adjacent to the wall of the tube, and a second low-resolution grid fills the interior of the tube. By using a high-resolution grid near the boundary of the IVC, adequate spatial resolution of the boundary layer is ensured, which is necessary for computing the wall shear stress accurately.

A rigid, three-dimensional model of the Celect filter is constructed using the computer-aided design features of the Overture software framework (https://computation.llnl.gov/casc/Overture/; Lawrence Livermore National Laboratory, Livermore, California). The starting point for developing the model is a set of high-resolution digital photographs (**Fig 1a**) that capture the filter in a glass test tube with a 23-mm inner diameter (the same diameter as the model cava). The photographs are then imported into the GNU Image Manipulation Package (http://www.gimp.org; GNOME Foundation, Groton, Massachusetts) where the filter geometry is extracted from pixel color and spatial coordinates. The data are then imported into Overture where the geometry is parameterized, and a computational grid of the filter is constructed. Additional measurements of the filter (eg, leg and tip sizes) are obtained using a digital caliper. The filter is discretized using approximately 50 body-fitted, overlapping grids. The spatial resolution of the grids is adjustable and is chosen to ensure adequate resolution of the flow throughout the entire domain (as determined by a grid resolution study, which is not shown here). The final computer model of the Celect filter is shown in **Fig 1b**. Note that the model does not include the attachment hooks, which fasten the Celect to the IVC. Once deployed, these hooks become embedded in the vein and therefore do not obstruct the flow.

Thrombi are modeled as rigid spheres of 0.5 mL and 1 mL, which are representative of the volumes studied in vitro by Wang et al (16). In vivo clots often assume random shapes with variable elasticity and porosity, but as noted by Swaminathan et al (13), spherical models represent, in some sense, a statistical average of irregular shapes.

Blood is modeled as a homogeneous, incompressible, Newtonian fluid with density $\rho = 1040 \text{kg/m}^3$ and dynamic viscosity $\mu = 2.57\text{e}10^{-3}\text{kg/(ms)}$. From the work of Swaminathan et al (13), the Newtonian approximation is appropriate for the current flow regime: non-Newtonian effects are minimal. The flow obeys conservation of mass and momentum as described by the incompressible Navier-Stokes (NS) equations (17). The single nondimensional parameter that characterizes the flow is the Reynolds num-