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Numerical and experimental study of the fluid flow through a medical device☆

M. Nicolás [a,b], V.R. Palero [a,b], E. Peña [a,b], M.P. Arroyo [a,b], M.A. Martínez [a,b], M. Malvè [a,b,c,*]

[a] Aragón Institute of Engineering Research (I3A), University of Zaragoza, C/María de Luna s/n, E-50018 Zaragoza, Spain
[b] Centro de Investigación Biomédica en Red en Bioingeniería Biomateriales y Nanomedicina (CIBER-BBN), Spain
[c] Public University of Navarra, Department of Mechanical Engineering, Energetics and Materials, Campus Arrosadía, E-31006 Pamplona, Spain

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ABSTRACT

The purpose of this paper is to verify a commercial software based fluid–structure interaction scheme for the inferior vena cava. Vena cava deep thrombosis (TVP) is a potentially deathly disease consequent to pulmonary thromboembolism (TEP). TEP consist in the obstruction of the pulmonary artery due to a blood clot traveling in the cardiovascular system and is treated with anticoagulants and inferior vena cava filters. Flow fields along the vena cava and an antithrombus filter were studied and compared with a Particle Image Velocimetry (PIV) based model to validate the numerical model. The results show that the fluid–structure interaction (FSI) models are valid and can be used to study the deformations in the inferior vena cava wall using patient-specific geometries.

1. Introduction

Pulmonary thrombotic embolism, known as PTE, is still a serious and frequent cardiovascular disease, despite the advances in surgical techniques and therapies. [1] Cardiovascular diseases are one of the main causes of death in developed countries and are an important subject of interest in the biomedical engineering research field. PTE is a significant clinical problem worldwide. In the United States alone, there are estimated two million cases per year [2]. Usually the main therapies used for the treatment of PTE are anticoagulation and fibrinolysis but sometimes they are contraindicated or ineffective, so it is necessary to use other techniques. Inferior vena cava filters have been shown to be effective in trapping embolized clots and preventing PTE [3]. They were designed for the first time in 1967 and since then their design has been improved considerably and their use has increased [4]. They have proved to be effective and secure in treating PTE but it still remains unknown which type of filter is the best. Ideally, the filter should be effective while being nonthrombogenic and nonimpeding to the blood flow, and should have the ability to break the clot once captured. In reality, the filter has to establish a balance between clot capture efficiency and flow impedance before and after clot capture [2].

While there have been a number of detailed hemodynamic studies of the aorta and major arteries, far fewer have been done in the major veins, such as the inferior vena cava (IVC) [5]. Previous experimental and computational studies have investigated the hemodynamic effects of IVC filter placement and embolus capture rate in simplified IVC geometries [6]. Many in vitro studies have been performed using optical methods such as particle imagine velocimetry [7–11]. [12,13, and [14] have studied flow fields surrounding a vena cava filter using a noninvasive technique called photochromic. [15,16, and [17] validate numerical results with the experimental 2D velocity fields obtained with PIV [18].

A more complex study was developed by [3] where numerical models were created with different commercially available filters and different clot shapes, and an in vitro experiment was developed using digital particle imaging velocimetry technique in order to compare the theoretical results obtained with the in-vitro experiments. In-vitro experiments are effective to study the filter flow dynamics but they also have setup limitations that sometimes do not allow creating very realistic scenarios. In-vitro experiments are a useful tool used to validate numerical models.

Numerical studies on vena cava filters are normally focused on hemodynamic aspects, neglecting the interaction between blood flow, venous walls and the filter. [18], and [19] evaluated the flow hemodynamics of the TrapEase and Celect vena cava filters using three dimensional computational fluid dynamics, including simulated thrombi of multiple shapes, sizes, and trapping positions. The study was performed to identify potential areas of recirculation. [2] developed a numerical model that characterized the hemodynamics of the flow around a Greenfield Vena Cava filter and that also wanted to determine the clot capturing efficacy.

The computation of fully coupled fluid flows with structural interactions is a rapidly evolving discipline that has been given increased attention in recent years [21]. FSI analysis is very important when the structure undergoes large deformations resulting from the presence of a fluid. FSI studies in the inferior vena cava are very important, which

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* Corresponding author at: Public University of Navarra, Department of Mechanical Engineering, Energetics and Materials, Campus Arrosadía, E-31006 Pamplona, Spain.
E-mail address: mauro.malve@unavarra.es (M. Malvè).

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to our knowledge have not been performed before. The inferior vena cava undergoes large deformations during Valsalva maneuver and the presence of a filter affects drastically the deformations that occur in the vena, so it is very important to start considering the IVC as a subject of FSI studies. Much has been accomplished in FSI modeling research since the early 1990s, and a good portion of that FSI research has been directed towards arterial fluid mechanics [22]. There are a number of FSI finite element analyses in cardiovascular diseases such as arterial stenosis [23–26], studies on left ventricular flow [27] and others in abdominal aortic aneurism [28].

Other authors such as [29] compare FSI with CFD models to study the differences between the two approaches. However, there are no FSI publications on inferior vena cava studies. [30] developed a computational rigid model of the inferior vena cava to study the hemodynamics of an unoccluded and partially occluded IVC and stated that a computer model that accounts for the fluid–structure interaction between the flow and the vessel/thrombus would provide a more realistic model. An important feature of the inferior vena cava to study is its predisposition to undergo large displacements. The blood flow depends on the vena geometry, and the deformation of the vena depends on blood flow. For that reason, the equations governing the blood flow and vena deformation need to be solved simultaneously, with proper kinematic and dynamic conditions coupling the two physical systems [22]. FSI analysis requires considerable computational power to run [31], so it is important to investigate if its use is justified over CFD analysis.

In this study, an in-vitro model is used to verify a commercial software based fluid–structure interaction scheme for the inferior vena cava. The velocity profiles of both numerical FSI and experimental PIV models are compared.

2. Materials and methods

2.1. Geometries and numerical grid generation

Computer-aided design models were created using the commercial software Rhinoceros (Robert McNeel and Associates). There are three separate CAD models to be analyzed as it can be seen in Fig. 2. First, a 12 mm diameter, 1.6 mm thick and 46 mm long idealized cylindrical vena cava was modeled. Second, a model that includes an antithrombus filter attached to the vena wall was designed. The filter was modeled by taking micrometer measurements to help as a guide. The angles

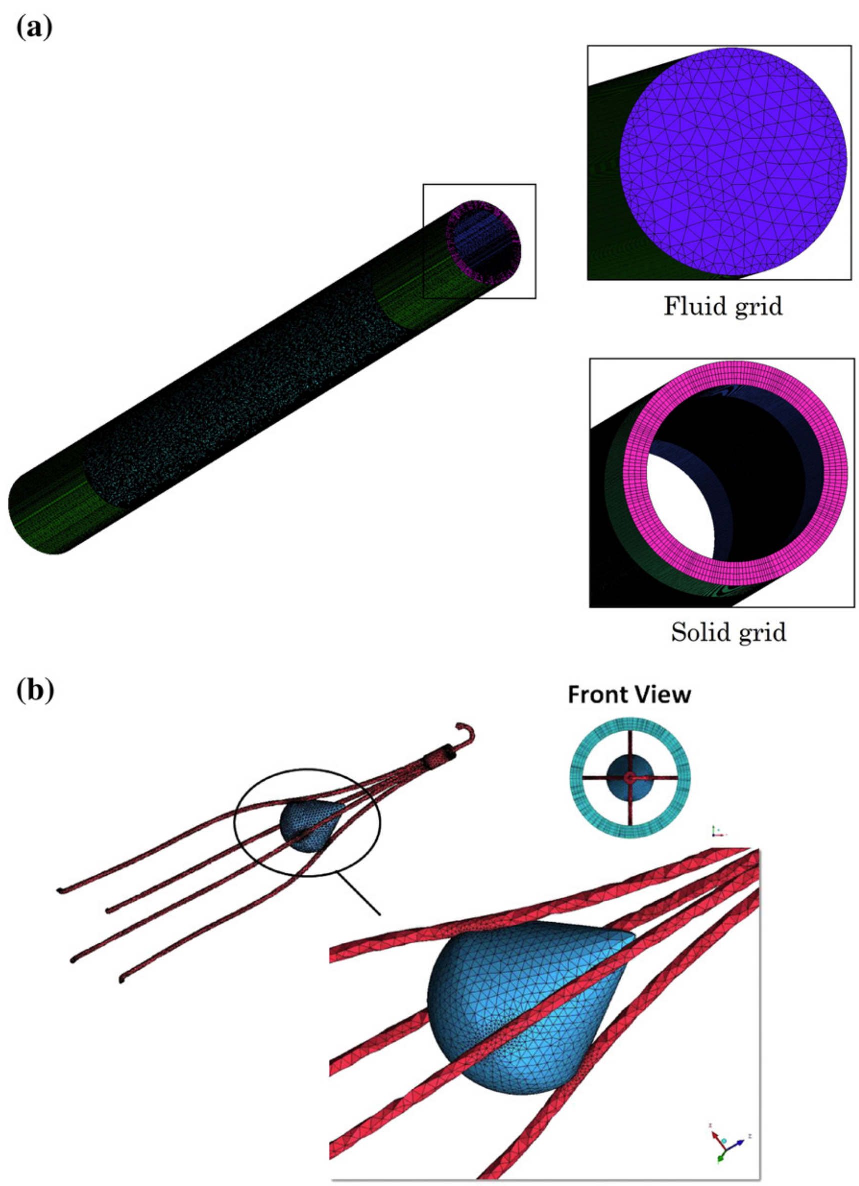

Fig. 1. a) Fluid and solid mesh for the empty vena model, b) Solid mesh for the IVC filter and clot.