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A SYSTEMATIC LITERATURE REVIEW ON THE USE OF FLUID-STRUCTURE INTERACTION SIMULATION FOR SYSTEMS OF BLOOD FLOW THROUGH ARTERIES WITH STENTS

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Abstract. *This article reviews the literature on applying Fluid-Structure Interaction (FSI) models to simulate blood flow in vessels with stents. Computational Fluid Dynamics (CFD) is growing as an analysis and support tool in cardiovascular medicine, helping to assess the severity of stenosis and aneurysms, allowing the planning of interventions such as bypass or stent placement as well as assisting in the stent's design to improve its performance. However, CFD simulations considering rigid structures do not capture some effects due to the elastic properties of the blood vessels and their interaction with the stent's material, which reduces its accuracy. Thus, FSI is the alternative to modeling the flow and deformation of materials as well as the interaction between them. To this end, the research aims to evaluate the potential application of hemodynamic models using FSI for the study of stents. The development of this study involves the selection of keywords, a search for articles in the database Scopus and the determination of inclusion and exclusion criteria. Respecting that, 29 articles were selected and analyzed, then classified and cataloged in three categories: application, type of blood vessel, and type of stent. The usefulness of FSI was verified and computational resource requirements, implementation strategies, and future directions of FSI for cardiovascular applications were discussed. It was concluded that using FSI techniques can reduce the costs and time associated with testing physical prototypes, reducing the need for animal tests, and allowing more efficient and safer prototypes to be developed and tested rapidly. Finally, the review emphasizes the need for further studies on the promising use of FSI in the simulation of stent systems to improve the models currently used and propose more accurate and universal validation strategies.*

Keywords: *Stent. Fluid-Structure Interaction, Hemodynamics, Computational Fluid Dynamics, Systematic Literature Review.*

1. INTRODUCTION

Studies regarding Fluid-Structure Interaction (FSI) emerged as a valuable tool in cardiovascular engineering over the last 20 years. FSI couples Computational Fluid Dynamics (CFD) and finite element analysis (FEA), allowing the investigation of fluid and structure behaviors and how they affect each other. The traditional CFD, using finite volume method, presents limitations regarding the exploration of challenges in cardiovascular engineering because it cannot represent how the fluid responds to an adjacent structure that has been deformed by the fluid pressure or other forces, Mendez V. et al. (2018). The elasticity and complacency of the blood vessels are intrinsic characteristics of the circulatory system, but they are not well modeled by the CFD method. In the same way, FEA methods cannot model the structural response to fluid dynamics if the fluid's physics is not known and is inherently dependent on the behavior of the structure itself. FSI uses CFD based in established finite volume and computational methods of structural FEA and, with that, couples physics of the fluid and structural domains by means of CFD and FEA solvers, Borowski F. et al. (2018).

FSI models can be implemented on patient-specific geometries created using data from magnetic resonance or computed tomography, Wang L. et al. (2018). The scan slices of 2D images are stacked and mixed, as shown below in Figure 1, creating a patient-specific 3D geometry.

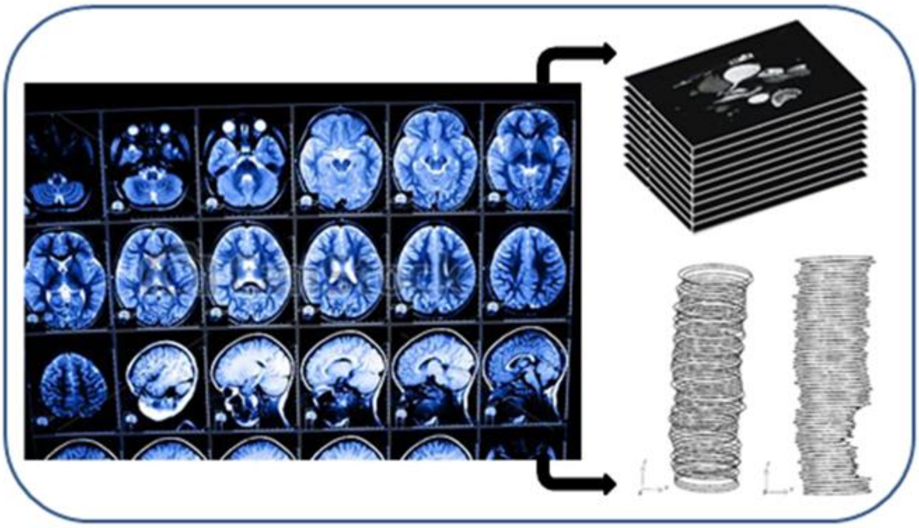


Figure 1. 3D image buildup. Source: EAE, 2023.

These methods are well established in cardiovascular CFD and are being used to create these precise models. FSI also allows studies on physical phenomena that are not easily measured and are relevant factors in the initiation, progress, diagnosis, and treatment of the disease. For example, the direct measurement of wall shear stress (WSS) in a blood vessel inside the body is impossible, but its value is significant. A pathologically low WSS is an important risk factor for the development and progression of arteriosclerosis and, if it is too high, blood clogs can occur, ones that can detach from the artery wall and possibly block blood circulation in other points, He F. et al. (2017). FSI allows clinical teams to consider the impact of parameters, as WSS, and make decisions about treatments based on patient-specific models, Drewe CJ. et al. (2017).

One of the diseases that can be prevented by analyzing WSS is arteriosclerosis, a condition that affects arterial blood vessels by forming plaques attached to the interior artery wall, caused by blood coagulation inside the vessel, reducing or even blocking circulation. When blood flow is reduced in the coronary arteries, angina (chest pain) can be felt. This symptom develops during physical exertion or emotional stress, when the cardiac muscle needs more oxygen, Simão M.F.R. et al. (2017a). In patients presenting bad blood circulation, caused by limited blood flow in coronary arteries, stent or angioplasty using a balloon can be used as medical therapy, Gottschall (2009).

Coronary stents are small tubes made of wire mesh that provide support to sustain the damaged artery wall, reducing stenosis, as Figure 2 below. However, intra-stent restenosis (ISR) can occur, closing the vessel again, which continues to be a common issue for various stent designs, leading to different stenosis rates, Jayendiran et al. (2018). Besides, patients presenting coronary plaques are not allowed to submit to angioplasty using a balloon or a stent, due to the small size of the coronary arteries or the complete blockage that cannot be crossed by the balloon. This way, angioplasty and stent implant must be considered when one or more arteries become narrowed, Simão M.F.R. et al. (2017a).

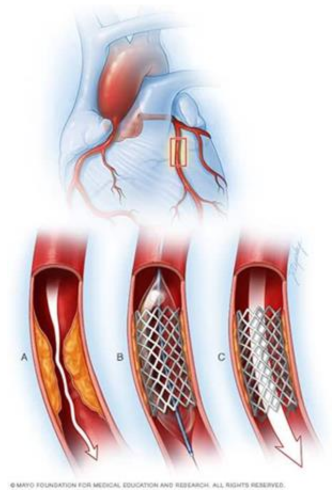


Figure 2. Stent implantation. Source: Dubey, 2022.

Depending on the stent's design, the arterial response to stent implantation can change from one patient to another, changing the blood flow and consequently raising their arterial pressure, Maria G.C. Nestola et al. (2021). Simple changes in configuration can reduce vascular lesion and formation of thrombosis. Thus, disparity on stent's performance can be attributed to multiple factors, such as type of vascular lesion, stent material and constructive form. The type of stent used to treat clogging is a predominant factor that affects stenosis, Lee et al. (2020).

After all, computational models of fluid dynamics (CFD), including fluid-structure interaction, are used to evaluate the hemodynamic impact on stent implementation. Hence, with the objective of understanding the use of stent models in FSI simulations, this paper presents a systematic literature review, according to the protocol presented by Dresch et al. (2015), about the subject "Fluid Structure Interaction (FSI) on stents". This review highlights various aspects such as stent types, software used in simulations, the applications of stents, and the respective pathologies addressed in the selected articles.

2. METHODOLOGY

To elaborate the systematic literature review, the method proposed by Dresch et al. (2015, cap. 6) was followed, which compiled protocols from different authors, and after that, the review protocol was elaborated as presented in *Table 1* below.

Table 1. Protocol used for the systematic review.

Conceptual Framework	Understand the application potential of hemodynamic models using Fluid Structure Interaction (FSI) for the study of stents.
Context	Blood flow in circulatory system. FSI models represent the advance related to models using pure CFD.
Horizon	Studies published after 2010.
Theoretical currents	Computational Fluid Dynamics versus Fluid Structure Interaction.
Idioms	English
Review question	What are the benefits of Fluid Structure Interaction (FSI) application in arterial stents studies.
Review strategy	***( ) Aggregative*** ***(X) Configurative***
Search criteria	***Inclusion criteria:*** Fluid Structure Interaction or CFD applied to arterial stents during its use. ***Exclusion criteria:*** Applications that are not hemodynamic models with stents, studies that approach only the installation process and not its performance during the use.
Search terms	Stent, CFD or Computational Fluid Dynamics OR Numerical Simulation, Fluid Structure Interaction OR FSI.

	Search sources		
Data base	***Annals***	***Internet***	***Other***
( ) Capes periodics	( ) ENEGEP	( ) Academic Google	( )
( ) EBSCO	( ) Cobem	( )	( )
( ) Scielo	( )	( )	
(x) Scopus / Elsevier		( )	

Source: Elaborated by authors.

2.1 **Bibliometric analysis**

The first three terms used for the systematic review were selected by seeking the objective of the search. The first keyword "STENT' was selected for keeping the research focused on stents; the others such as "CFD", to emphasize the CFD simulation and the fluid flow; and "FSI" to specify the simulation about fluid structure. Ultimately, the research was finalized including 40 articles.

To broaden the scope of articles for the research, the software "VOSviewer", a tool for visualization and mapping of researches, was used, Van Eck, (2020). That way, it was possible to analyze ramifications and combinations of key words, as shown in the image below. With branching, it is possible to analyze many words connected to the main ones used in the research, such as Shear Stress, Computational Fluid Dynamics, Biological Model, and Geometry, all of which are relevant to the topic of stents.

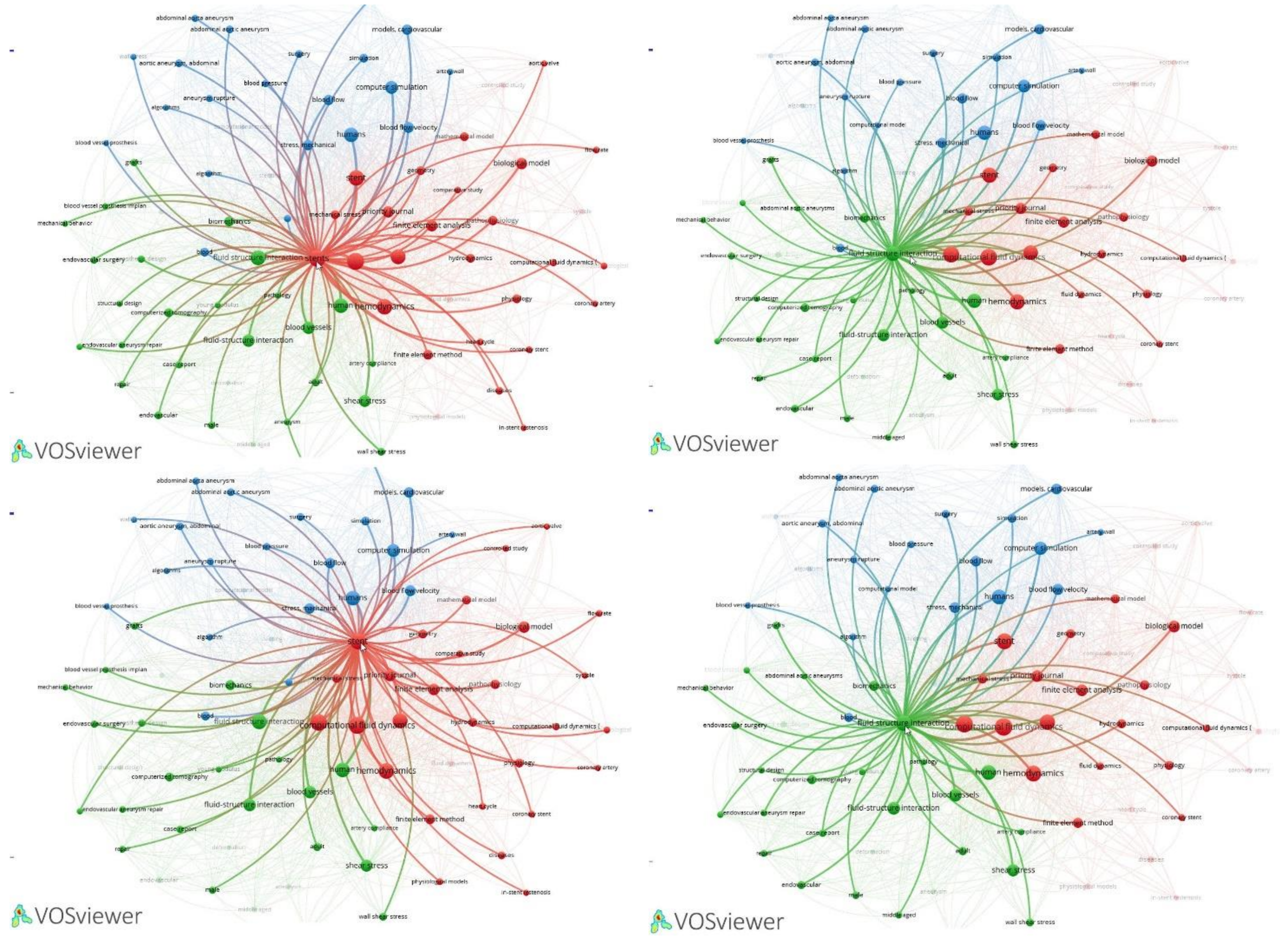


Figure 3. Keyword network on VOSviwer. Source: Elaborated by authors.

Then, by using the VOSviewer tool, it was possible to obtain a better ramification for the search: "STENT', CFD OR COMPUTATIONAL FLUID DYNAMICS OR NUMERICAL SIMULATION", and "FLUID STRUCTURE INTERACTION OR FSI". By using these terms and the strings 'OR', the work was simplified, considering some articles diverge on the writing of the words. As a result, the search was summarized using the platform Scopus, where 69 articles were found. Further filters were applied to refine the result, reaching a total of 29 articles for the analysis. The process is shown in the next table 2.

Table 2. Filters used to select the articles.

Filters	*Number of articles found*
Keywords	69
Works referring to conferences or book chapters were excluded	53
Removing articles published before 2010	39
Total articles available for the analysis (complete only)	29

Source: Elaborated by authors.

After the filters, the articles were assessed, tabulated, and numbered on an electronic spreadsheet. Subsequently, the identified articles were thoroughly read, and some important points were identified, as shown in Figure 4 below.

Article Number	Validation	Blood Vassel	Stent Material	Softwere (CFD / FSI)		Fluid	Velocity Profile	Extra Information	Pathology	Parameters (OSI, WSS, others)
2	Simulated with Literature	Aorta	nickel-titanium alloy, a hyperelastic material with coupled temperature parameters and mechanical parameters.	Ansys (Fluent)	Abaqus	Non-Newtonian	Pulsating (input/output)	Different dimensions of stents	Thrombosis	Von-Misses, stent validation
4	in silico	Main Aorta	Uninformed	Uninformed	Uninformed	Newtoniano	Pulsating	Used rim models	Thrombosis	Mittal's method
5	in vivo	Trachea	Silicone	Ansys (Fluent)	Ansys (Mechanical)	Newtoniano	Turbulento	Trachea Stent Models	Tracheal Disorders	Incompressible and turbulent flow
7	in vitro	Thoracic aorta	Elastic	Ansys-ICEM 16.1	Ansys-ICEM 16.1	Non-Newtonian	Windkessel	Windkessel Parameter Information	Aortic Diseases	OSI / TAWSS
8	in vitro	Aorta	Rigid polymer	Uninformed	Uninformed	Newtoniano	Pulsating at the entrance and Windkessel at the exit	Heart valve performance and compare different hyperelastic soft tissue models	evaluate the blood-tissue interaction of heart valves	Equations to formulate the FSI problem with Lagrange coordinates
11	in vitro	Heart Aorta	Hyper elastic material	FlowVision	Abaqus	Newtoniano	Pulsating	Simulation with stents in different situations	Aortic Calcification	OSI / WSS / Von Misses
12	-	An idealized vase model	Metal - Polymer	Ansys	Ansys	Non-Newtonian	Pulsating	Two Stents with different materials	obstruction	Von Misses tension on the Stent
13	in vitro	Several Applications	-	-	-	Non-Newtonian	-	Systematic review of more than 1000 journal articles	Aortic Diseases	OSI / WSS
14	-	Thoracic aorta	-	Ansys	Ansys	Non-Newtonian	Windkessel	Model drawn and not taken from an examination, showing the drawing of the Aorta	Biomechanical implications of protrusion segment (PS) of the stent	OSI / WSS
15	In Vivo	Left subclavian artery	-	Ansys	Ansys	Non-Newtonian	Windkessel	Implemented physiological pressure waves	The Impact of Left Subclavian Artery (LSA) Coverage During Endovascular Thoracic Aortic Surgery	OSI in different parts
16	-	gallbladder	Plastic	-	-	-	Windkessel	predict the replacement period of a given patient and improve the quality of his life.	Gallbladder removal (cholecystectomy)	-
17	in vivo	Cerebral Aorta	4 different materials	Uninformed	Uninformed	Newtoniano	Pulsating / Turbulent	4 different models, containing measurements for the construction of these models, points for analysis	Celebral aneurysm	WSS, OSI, Pressure
18	in vitro	Cilindro Padrão	Magnesium WE43	Ansys	Ansys	Not informed	Pulsating	numerical simulation and physical experiments, stent degradation in an environment similar to human blood vessels	stent degradation in a dynamic environment	WSS / FSI
20	in vivo	Heart Aorta	Uninformed	Ansys	Ansys	Newtoniano	Pulsating	Promotes the development of thrombi modulating the local flow pattern which reduces wall stress while maintaining permeability of the side branches.	Aneurysms	WSS / OSI / RRT / Pressure on the model wall due to the Stent
21	in vivo	Standard Cylinder	Iron	Uninformed	Uninformed	Non-Newtonian	Pulsating	Two stent models were analyzed, one Palmaz–Schatz and another idealized (spring)	Aneurysms	WSS on the Artery wall
22	in vivo	Arteria Coronaria	Aço	SimVascular	SimVascular	Non-Newtonian	Pulsante	Model drawings of different stents	Impact that occurs using different stents	Analysis FFR
25	in vivo	Aorta principal do Coração	-	Ansys (Fluent)	Abaqus	Newtoniano	Pulsante , Windkessel	Modelos com diferentes obstruções	Aortic Obstruction	Pressure and fluid behavior
26	in vivo	Uretra	Não informado	Abaqus	Abaqus	Newtoniano	Fluido Incompressivel	Fluido não é sangue e sim urina, a influencia do stent com a urina	Analisar melhor stent para Uretra	WSS , Mooney-Rivlin Model , Neo-Hookean Model

Figure 4. Example of electronic spreadsheet. Source: Elaborated by authors.

The topics analyzed in the 29 articles were:

Article number – all articles were numbered according to the search order made on Scopus.

Validation – the validation made on the presented geometry was analyzed, which can be *in vivo*, when it is observed in living organisms, or *in vitro*, referring to the studies made using an idealized model (3D) of the problem.

Blood vessel – identifying the type of geometry analyzed in the study, being a coronary artery or any other blood vessel of the human body that can have a stent implanted.

Stent material – the materials of the stent in this case are normally made of surgical steel, but some variations can be found, such as chrome, silicon or some new alloy that's being studied.

Software (CFD/ FSI) - the softwares used for the fluid dynamics (CFD) and structural analysis (FEA) simulations were catalogued.

Fluid – this is one of the important points to be analyzed for the blood can be considered as a Newtonian fluid, where its properties don't change according to the temperature shift, or as non-Newtonian fluid, where its properties shift in the same situations. Many articles tend to use the blood as Newtonian fluid, mainly on geometries with bigger areas or for a previous analysis. Besides, the best indication for the blood behavior is to consider it as a non-Newtonian fluid.

Velocity profile – every simulation needs input data on the system. With that, the objective of this topic is to catalogue the types used in different geometries, such as a pulse profile, a sinusoid or even something more specific as Windkessel, the most used in hemodynamic analysis.

Extra information – this topic has the objective to catalogue points that called attention in the article that was judged important for a general analysis of the problem.

Pathology –the kind of disease in the case or that the patient can end up developing if not implanted the stent.

Parameters (OSI, WSS, others) - this last analyzed topic refers to the presented results on each article to base the analysis of the results for the problem in the case.

3. RESULTS

After the first analysis and cataloguing of the main points, 29 articles in total were selected. Those are summarized in the next *Table 3*.

Table 3. Selected articles.

N°	*1º Autor*	*Title*	*Year*	*Highlight points*
2	*Liu, X.*	*Fluid-Structure Interaction Analysis on the Influence of the Aortic Valve Stent Leaflet Structure in Hemodynamics*	*2022*	*Different stent dimensions*
4	*Bailoor, S.*	*Prosthetic Valve Monitoring via In Situ Pressure Sensors: In Silico Concept Evaluation using Supervised Learning*	*2022*	*Different aorta models*
5	*Kamran Hassani*	*Biomechanical analysis of tracheal stent during cough reflex*	*2022*	*Trachea stent models*
7	*Qiao, Y.*	*Fluid-structure interaction: Insights into biomechanical implications of endograft after thoracic endovascular aortic repair*	*2021*	*Informations on Windkessel parameters*
8	*Maria G.C.*	*Fully coupled dynamic simulations of bioprosthetic aortic valves based on an embedded strategy for fluid-structure interaction with contact*	*2020*	*Cardiac valve performance and different hyper elastic tissue models.*
11	*Ghosh, R.P.*	*Numerical evaluation of transcatheter aortic valve performance during heart beating and its post-deployment fluid–structure interaction analysis*	*2020*	*Simulations with stents in different situations.*
12	*Lee, W.*	*Numerical study to identify the effect of fluid presence on the mechanical behavior of the stents during coronary stent expansion*	*2020*	*Two stents using different materials*
13	*Hirschhorn, M.*	*Fluid–structure interaction modeling in cardiovascular medicine – A systematic review 2017–2019*	*2020*	*Systematic review of over 1000 articles*
14	*Qiao, Y.*	*Biomechanical implications of the fenestration structure after thoracic endovascular aortic repair*	*2020*	*Drawn model not acquired from a medical exam.*
15	*Qiao, Y.*	*A primary computational fluid dynamics study of pre-and post-tevar with intentional left subclavian artery coverage in a type b aortic dissection*	*2019*	*Physiological wave pressures implemented*
16	*Kuchumov*	*Biomechanical model of bile flow in the biliary system*	*2019*	*Predict the substitution period of a stent*
17	*Jayendiran*	*Fluid-structure interaction (FSI) analysis of stent-graft for aortic endovascular aneurysm repair (EVAR): Material and structural considerations*	*2018*	*4different stent models using its modeled geometries*
18	*Liu, D.*	*Degradation mechanism of magnesium alloy stent under simulated human micro-stress environment*	*2018*	*Stent's degradation in an environment similar to human blood vessels*
20	*Wang, S.*	*Influence of overlapping pattern of multiple overlapping uncovered stents on the local mechanical environment: A patient-specific parameter study*	*2017*	*Thrombi development modulating the pattern that reduces wall shear stress*
21	*Simão, M.F.R.*	*Structural analysis of two different stent configurations*	*2017*	*Analysing two stent models, one Palmaz – Schatz and the other an idealized (springs)*
22	*Simão, M.F.R*	*Behaviour of two typical stents towards a new stent evolution*	*2017*	*Drawings of different stent models*
25	*Taelman, L.*	*Differential impact of local stiffening and narrowing on hemodynamics in repaired aortic coarctation: an FSI study*	*2016*	*Models with different obstructions*
26	*Gómez-Blanco, J.C.*	*Fluid Structural Analysis of Urine Flow in a Stented Ureter*	*2016*	*Urine as a fluid and the stent's influence*
28	*Rinaudo, A.*	*Biomechanical implications of excessive endograft protrusion into the aortic arch after thoracic endovascular repair*	*2015*	*Building a model of an idealized aorta for stent analysis*
30	*Kabinejadian, F.*	*Effects of a carotid covered stent with a novel membrane design on the blood flow regime and hemodynamic parameters distribution at the carotid artery bifurcation*	*2015*	*Analysis of a new membrane for stents application*
32	*Selvarasu, N.K.C.*	*Effects of elastic modulus change in helical tubes under the influence of dynamic changes in curvature and torsion*	*2014*	*Changing the elasticity model of the stents, comparing the tensions that cause restenosis*
33	*Chiastra, C.*	*On the necessity of modelling fluid-structure interaction for stented coronary arteries*	*2014*	*Analysis of the tensions on the wall with two stents of different materials*

34	*Bokov, P.*	*Implementing boundary conditions in simulations of arterial flows*	*2013*	*A simulation with no stent and the other with a common one, used to unblock blood vessels*
35	*David Roy*	*A fluid-structure interaction-based numerical investigation on the evolution of stress, strength and rupture potential of an abdominal aortic aneurysm*	*2013*	*Research related to the artery wall, properties and limitations and point of rupture*
40	*Malvè, M.*	*Computational fluid-dynamics optimization of a human tracheal endoprosthesis*	*2012*	*The silicon stent Dumon is widely utilized for trachea diseases treatments*
41	*Vahidi, B.*	*A biomechanical simulation of ureteral flow during peristalsis using intraluminal morphometric data*	*2012*	*Analysis and use of stent to better the fluid flow*
44	*Roy, D.*	*A literature review of the numerical analysis of abdominal aortic aneurysms treated with endovascular stent grafts*	*2012*	*Use of external stent*
46	*Malvè, M.*	*Numerical modeling of a human stented trachea under different stent designs*	*2011*	*Analysis of two stents in different positions in the model*
54	*Zhonghua Sun*	*Fenestrated stent graft repair of abdominal aortic aneurysm: Hemodynamic analysis of the effect of fenestrated stents on the renal arteries*	*2010*	*Two exams with different aneurysms, adding stent and evaluating the improvement*

Source: Elaborated by authors.

Analyzing the above-mentioned articles, it can be observed the broad utilization of stents in different situations. Cases of their use in the trachea were found, such as the model seen in Figure 5a below, for people with severe infections and to aid in airway obstruction relief, as reported by Hassani et al. (2022) and M. Malvè et al. (2011), who analyzed tracheal deformability after prosthetic implantation under normal breathing and coughing using a fluid-structure interaction (FSI) approach.

Moreover, complete stent geometries were found, as shown in Figure 5b, with dimensions and materials used, and idealized stents being studied for future use, as described by Liu et al. (2010). M. Malvè et al. (2012) also proposed changing the design of the stent ends to improve flow through the prosthesis, modeling the tracheal wall as a hyperelastic solid material with different designs. The result was the reduction of local vortices at the stent ends, avoiding recirculation during breathing.

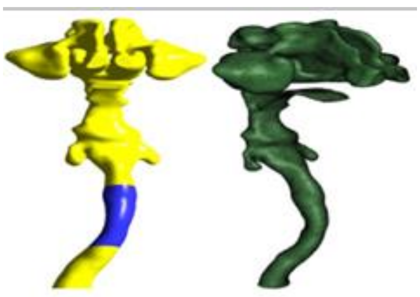


Figure 5a. Trachea model.
Source: Hassani et al. (2022)

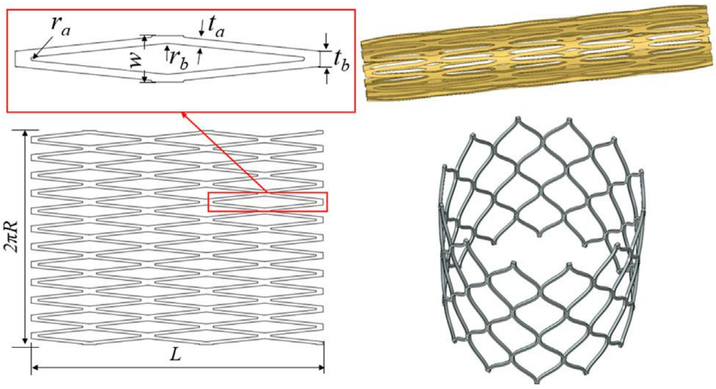


Figure 5b. Stent drawing. Source: Liu et al. (2010)

In Qiao Y.M. et al.'s article (2021), the importance of Windkessel boundary conditions and examination results for the understanding of blood dynamics in the aorta, as shown in Figure 6a, can be highlighted. Additionally, taking the elasticity of the aortic wall into account is crucial, as the assumption of a rigid wall fails to predict energy dissipation and pressure at specific points in the aorta. Through simulations with stents in different situations, such as open, closed, and with possible restenosis, it is possible to evaluate the behavior of blood flow and make more precise clinical decisions, as shown in Figure 6b, Ghosh et al. (2020).

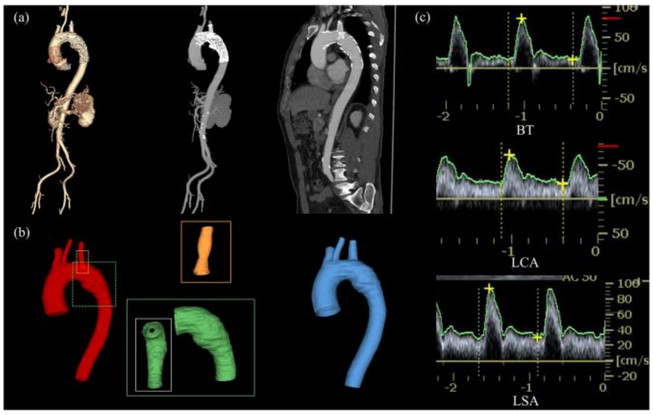


Figure 6a. Medical exam model.
Source: Qiao Y.M. et al. (2021)

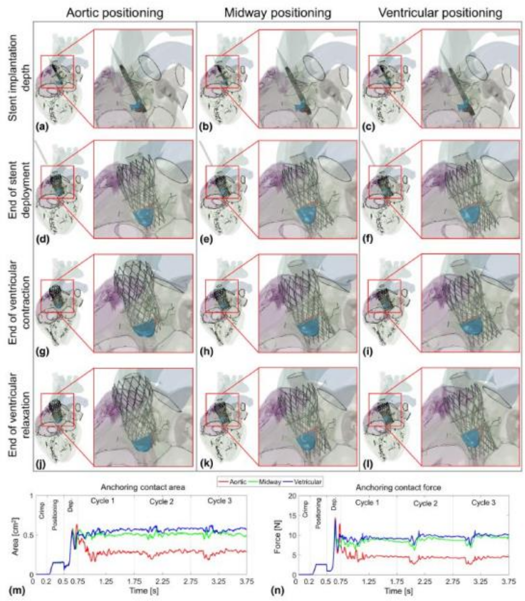


Figure 6b. Stent in different situations
Source: Ghosh et al. (2020)

Simão M.F.R. et al. (2017b) used different stent configurations, such as the Palmaz-Schatz and an idealized design, which were investigated. A finite element model was used to study the two geometries under combined loads, and a dynamic computational fluid model based on fluid-structure interaction was developed to examine the plate and arterial wall reactions in a stented artery segment. These models determined the stress and displacement fields of the two stents under internal pressure conditions. The results suggested that the stent designs shown in Figure 7 cause alterations in vascular anatomy that adversely affect arterial stress distributions within the wall, which in turn affects vessel responses such as restenosis. Hemodynamic analysis shows that the use of a new stent geometry with four longitudinally incorporated beams suggests a better response to progressive plaque growth.

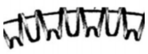
Stents	Physical characteristics	Stents	Physical characteristics
Palmaz-Schatz  Approval: 1997	Expandable diamond mesh slotted tubes articulated at specific points by straight link elements	Jostent Flex  Approval: 2001	Flex sinusoidal ring modules linked via alternating flexible spiral and slightly curved link elements. Struts are smooth with rounded edges
Sorin Carbostent (JANUS)  Approval: 2006	Slotted tube multicell design which is MRI safe with a stent strut thickness	Cypher  Approval: 2003	Sinusoidal ring strut modules linked by flexible "N"-shaped flex segments
TAXUS Express  Approval: 2004	Modular ring strut pattern. Microelements linked via straight articulations to long, wide sinusoidal macroelements	Multi-link Vision (MLV)  Approval: 2003	Corrugated Multi-Link five crown rounded corner zigzag ring module design linked via single-turn link elements
Gianturco-Roubin II  Approval: 1996	Flat wire coil attached to a single longitudinal strut	NIRFLEX  Approval: 2003	Sinusoidal ring modules consisting of alternating long and short crowns linked via "Z"-shaped elements

Figure 7. Stents models. Source: Simão, M.F.R. et al. (2017a)

Bahman Vahidi (2012) conducted a biomechanical analysis to improve our understanding of the peristaltic transport phenomenon of urine from the kidney to the bladder, using a deformable wall with the FSI concept applied to the model wall. Zhonghua Sun (2010) investigated the hemodynamic effect of two fenestrated stents in the renal arteries using the fluid-structure interaction method. Two real patient models in different states of aneurysm were used, with the stent added to the model to obtain the necessary results for fluid dynamic analysis in the model.

4. CONCLUSIONS

As computational resources become readily available and advanced, and imaging modalities continue to improve in resolution, fully coupled FSI studies will continue to tend towards becoming more common in cardiovascular engineering. Vessel wall mechanics and fluid dynamics play an important role in mediating cardiovascular disease. Any factor that modulates vessel wall, mechanical or fluid dynamic forces, can affect it. Coronary arterial motion is one such factor. Extensive research on the localized nature of atherosclerosis has led to the hypothesis that blood flow and patterns affect and modulate the processes that lead to atherosclerosis.

These issues are further complicated by the presence of variations in the modulus of elasticity that may be caused by atherosclerosis or stents. This effect of dynamic changes in geometry under pulsatile flow, conditions with variations in the local hemodynamic modulus of elasticity as seen in coronary arteries, is not fully understood. FSI studies are of particular use in cardiovascular engineering because many flexible structural systems, both native and synthetic, interact with blood. They are used in widely varied applications and provide information that could not easily be obtained through other numerical techniques or experimental tests. This review has demonstrated the use of FSI throughout the field of cardiovascular engineering, and computational resource requirements, implementation strategies, and future directions of FSI for cardiovascular applications were also discussed. Furthermore, the database to research could be used others like PubMed, Scielo or Academic Google.

5. ACKNOWLEDGEMENTS

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