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Comparison of Laminar and Turbulent *K*–Omega Shear Stress Transport Models Under Realistic Boundary Conditions Using Clinical Data for Arterial Stenosis

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Early diagnosis of cardiovascular diseases (CVDs), including arterial stenosis, enables targeted treatments that reduce CVD mortality. It is vital to improve the accuracy of early diagnostic tools. Current computational studies of stenosis use mathematical models, such as laminar and k–omega shear stress transport (SST) models, available in ANSYS *(Fluent and CFX),* OPENFOAM*, and* COMSOL *software packages. Users can adjust boundary conditions, such as inlet velocity and outlet pressure using user-defined functions (UDFs) with different expressions and constant values. However, currently there is no rule over what to impose at these boundaries, and previous studies have used various assumptions, such as rigid artery wall, one-way fluid–structure interaction (FSI) or two-way FSI, and the blood's Newtonian or non-Newtonian material properties. This variety in construction has associated deviations of the models from the clinical data and lessens the value of the models as potential diagnostic or predictive tools for medical practitioners. In this study, we examine arterial stenosis models, with severities of 20%, 40%, and 50%, compared with the healthy artery analyzed in terms of strain energy to the artery wall. Additionally, we investigate elastic walls using one-way FSI, comparing with laminar and k–omega SST. These boundary conditions are based on clinical data. The results regarding the strain energy (mJ) behavior along the artery wall show that the k–omega SST model outperforms the laminar model for short arterial segments and under the Newtonian assumption with a no-slip boundary wall and turbulent flow.* [DOI: 10.1115/1.4066258]

Keywords: k–omega shear stress transport (SST), laminar model, one-way fluid–structure interaction, strain energy, arterial stenosis

1 Introduction

Finding the appropriate method to develop computational models of the cardiovascular system is essential in order to generate acceptable results that enhance the understanding of the cardiovascular system and enable non-invasive diagnosis. Recent studies [1–5] used different computational techniques to investigate arteries applying some realistic and some unrealistic assumptions for the blood and the artery wall. Using the finite volume method (FVM), Roy et al. [1] modelled a stenosed artery with a 50–90% cross-sectional area reduction. The blood properties were solved using the Carreau-Yasuda non-Newtonian model, and mathematical boundary conditions were solved as transient analysis using C++ language. Their validated computational results show that severe stenosis with 90% arterial blockage with a laminar flow regime could lead to atherosclerosis. However, they suggested using the fluid–structure interaction (FSI) method to achieve realistic outcomes. Zhou et al. [2] assessed hemodynamic characteristics for athetosis using CFD methods, assuming that the blood is non-Newtonian (Carreau model) and comparing it to Newtonian. They found that the Newtonian properties of atherosclerosis do not reflect the rheological behavior of the blood, which could impact the main non-invasive diagnosis using the CFD method. Yi et al. [3] investigated the impact of atherosclerosis (stenosis) irregularity with the aim of quantifying the hemodynamic parameters for a patient-specific model using CFD methods using Fluent using Newtonian blood properties with laminar regime assumption. Their results suggested that surface roughness should be used to get better results for stenosis models so the wall shear stress results will be more clinically acceptable.

The FSI method is not widely used in cardiovascular diseases due to the high computer specification requirements for acceptable results [6,7]. Shahzad et al. [6] used the Casson model to investigate the hemodynamic effects of the blood flow (with non-Newtonian

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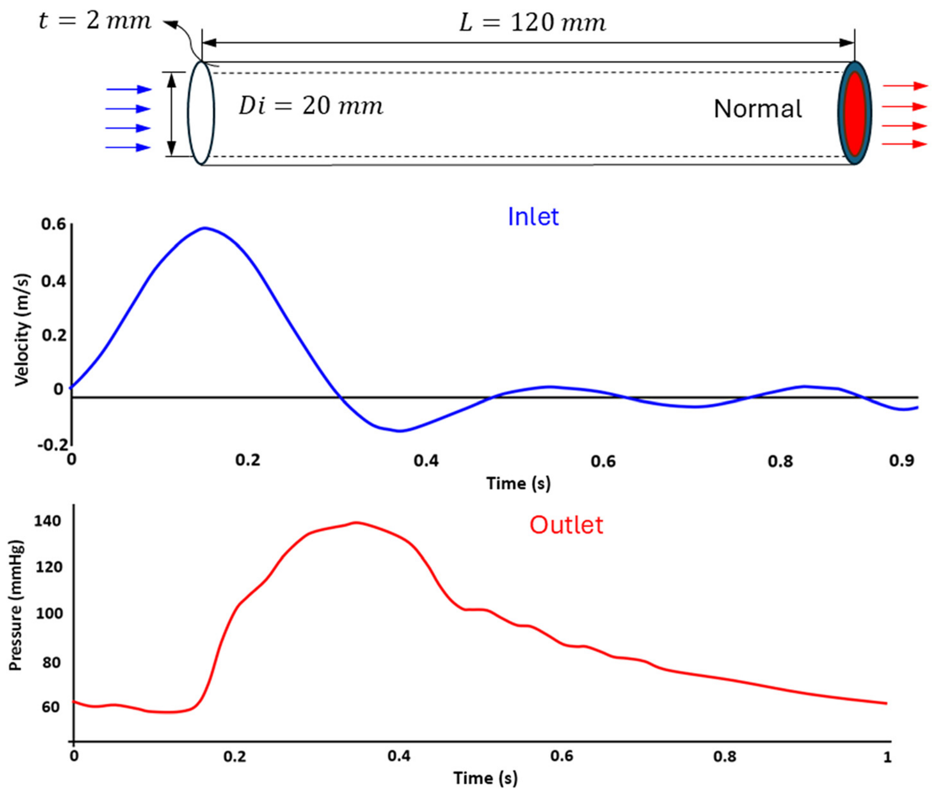

Fig. 1 The computational domain and the boundary conditions for the healthy artery (adapted from Ref. [4])

assumption) passing through an elastic wall using the FSI method with a Laminar flow regime. Their results indicated that rigid wall assumption creates higher wall shear stress contours than elastic artery assumption. Also, transitioning from a laminar to a transitional flow regime, the viscous forces inside the fluid increase, which retards the blood flow inside the artery. Therefore, several studies suggested using the FSI method with non-Newtonian [8] and Newtonian [9,10] blood properties to address the artery wall during abnormal blood flow due to cardiovascular diseases. Vignali et al. [10] studied the strain energy to understand the tissue function when it exhibits a hyperplastic and anisotropic response for the aorta geometry with ascending aneurysm using the FSI method. Their results show that using fully non-linear properties illustrated a more acceptable stress distribution for using the strain energy equation.

In this study, different artery blockages (20%, 40%, and 50%) were investigated using the laminar and *k*–omega $(\mathrm{k}-\omega)$ Shear stress transport (SST) Turbulence models using ANSYS FLUENT and applying the FSI method under the transient structural mechanical analysis to assess the strain energy response to disease development and compare it to that of a healthy artery.

2 Materials and Methods

In this study, ANSYS FLUENT was used to set up the physical for the CFD model using the laminar and turbulent flow regimes. As explored in the introduction section, this type of analysis was introduced using either low Reynolds numbers presenting laminar flow and others assumed the model turbulent flow regime. This is due to the following assumption if using steady flow in straight artery Reynolds number will be around 2000 and if we consider fully turbulent model it is around 4000, however, the calculated Reynolds number based on the inlet boundary conditions and Newtonian material properties is 3500 which is in the transitioning zone.

The artery, having a length of 120 mm, internal diameter of 20 mm, and thickness of 2 mm was induced by a velocity waveform at the inlet and pressure waveform at the outlet, as shown in Fig. 1.

Since the artery exhibits elastic material properties corresponding to the blood flow addressing the forward and backward waveforms, the FSI method relies on using the CFD results from ANSYS FLUENT for both laminar and turbulent regimes. This will provide a better understanding of arterial compliance to track the artery expansion and contraction during the healthy condition and compare it to the development of arterial stenosis with different severities. The CFD calculations were done using a fixed type and user-specified method with the number of time steps equaling 1000, a time-step size of 0.001 s, with maximum iterations of 30 and 10 reporting intervals.

The transient structural analysis was performed after generating the ANSYS FLUENT results to achieve the one-way FSI method. The artery wall properties were shown in Table 1 using an isotropic elastic model adapted from Al-Rawi et al. [11] and Al-Rawi [12].

The artery walls were meshed using the Sweep method with edge sizing of 50 divisions, soft and exhibiting no bias behavior to achieve the satisfactory Node number (N) and Elements (E), as shown in Fig. 2. The boundary conditions for the transient structural analysis were set as fixed ends and FSI interface for the inner layer of the artery, with a time-step 1×10^{-4} s for the step end time of 1 s.

The mesh independence study to achieve convergence is assessed to ensure the simulations are not dependent on the mesh size. The Initial mesh was created as coarse mesh for the healthy artery using the sweep method with changing the edge size using different number of divisions (20, 30, 40, and 50) as shown in Table 2 and

Table 1 The isotropic elastic artery wall material properties

Property	Value	Units	Symbol
Density	1100	kg/m^3	ρ
Young’s modulus	0.3	MPa	E
Poisson’s ratio	0.27		v

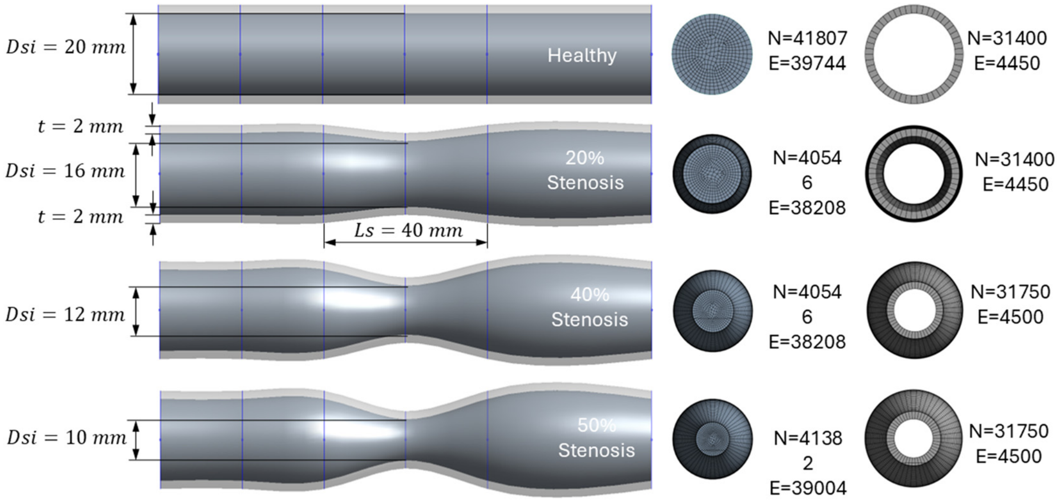

Fig. 2 The healthy condition and the three-stenosis severity 20%, 40%, 50%, and the mesh for the blood and artery wall

Table 2 The mesh test using different number of divisions

Number of divisions	Node	Elements	Shear stress (MPa)	Difference
20	5140	720	0.042	14%
30	11490	1620	0.049	8%
40	20360	2880	0.053	4%
50	31400	4450	0.055	-

Fig. 3. The mesh test was done to assess the shear stress values at the stenosis location for the healthy artery within the transient structural mechanical in ANSYS.

The mechanical stress in this study is assessed in terms of strain energy for the artery wall to analyze the shear forces exerted per unit area on the artery due to the blood pressure and velocity waveforms. Assessing strain energy behavior is important to determine the energy stored in a body due to deformation or disturbance related to the velocity and pressure waveforms and how the artery wall responds to these wave propagations.

Additionally, we assessed the situation in which the condition becomes fatal, in terms of the structural damage to the artery based on the FSI model during atherosclerosis diseases.

3 Results and Discussion

This study focuses on the FSI model, particularly the strain energy corresponding to the waveforms propagated along healthy and unhealthy arteries. Therefore, this study will provide the

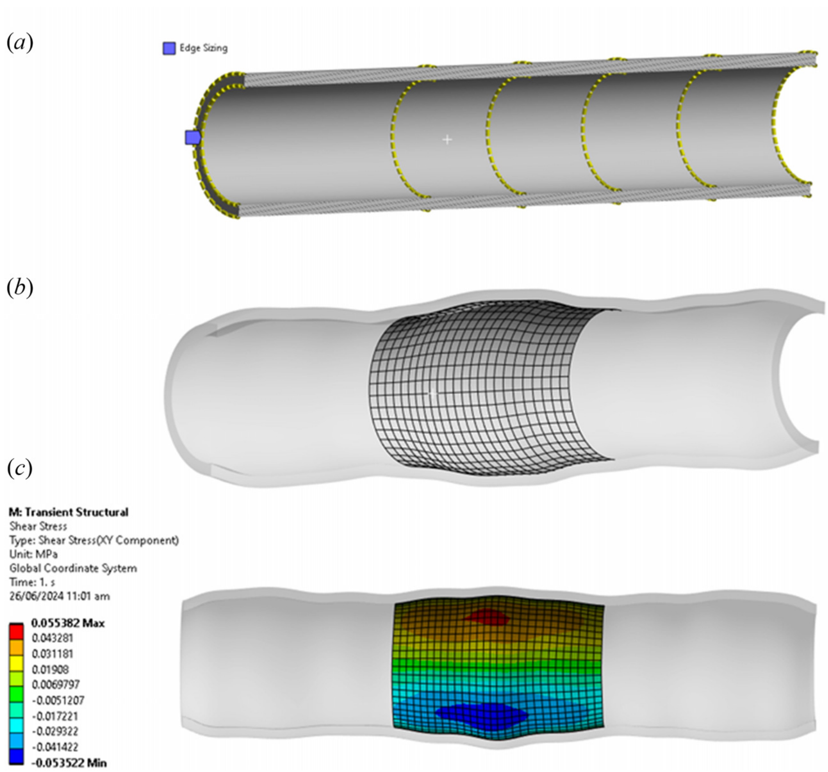

Fig. 3 (*a*) Number of divisions, (*b*) mesh at the stenosis location, and (*c*) shear stress at the stenosis location

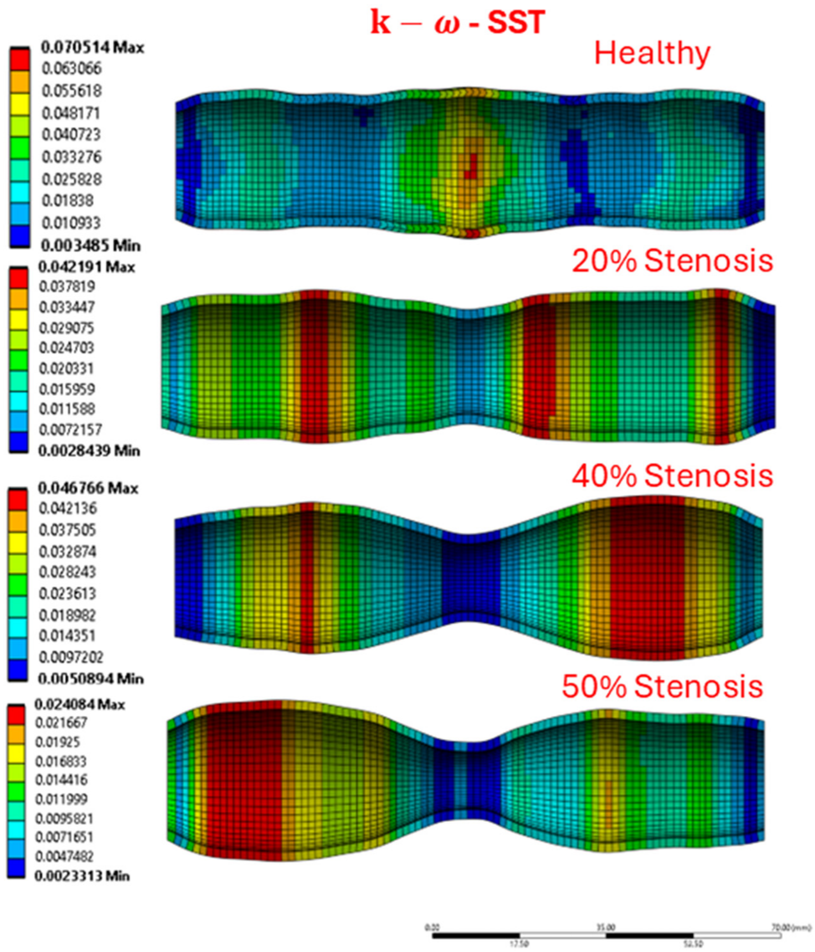

Fig. 4 The strain energy for the healthy and three stenoses (20%, 40%, and 50%) for *k*–omega model

relationship between strain energy and stenosis development in a straight artery and compare the results using *k*–omega SST and laminar models. Figure 4 shows the strain energy contours for the healthy and three stenosis models for the *k*–omega SST model.

Figure 5 shows the strain energy contours for the healthy and three stenosis models for the laminar model.

Table 3 summarizes the maximum and minimum values for the strain energy for each model and compares it to the healthy model. The results show a difference of 24% for the max value compared to 18.6% for the min values for the healthy model. However, the maximum differences will drop during the development of stenosis. The Reynolds number based on the inlet boundary conditions and material properties is around 3513.143 which indicates a transitional to turbulent flow regime, which is why the *k*–omega SST model is recommended for short arteries although it can be acceptable for longer sections.

The results show that increasing wall stress at the location of the stenosis is due to the disturbance created by the blood flow from a bigger cross section to a smaller one. These changes in the stresses impact the fluid–structure interface surface, which impacts endothelial functionality and causes atherosclerosis.

However, at the location of the stenosis, the wall stress is reduced, which leads to impairments in nitric oxide production, and causes injury to the fluid-structure interface layer. Therefore, the strain energy of the artery (along the whole length) during the stenosis development shows a drop of the maximum start value from 313.9 mJ to 272.17 mJ with clear fluctuation compared to the healthy model. These results were identical for both the *k*–omega SST and laminar models. When the stenosis reaches 50%, the fluctuation of the strain energy shows a low amplitude phasing off, as shown in Figs. 6 and 7. These results were identical for both models, the

Table 3 Maximum and minimum strain energy data (mJ)

	Laminar		*k*–Omega SST		Δ (%)	
Case	Max	Min	Max	Min	Δ max	Δ min
H	0.053582	0.0041333	0.070514	0.003485	24.01%	18.60%
20%	0.049079	0.0051315	0.042191	0.0028439	−16.33%	80.44%
40%	0.04677	0.0049767	0.046766	0.0050894	−0.01%	−2.21%
50%	0.024036	0.0023083	0.024084	0.0023313	0.20%	−0.99%

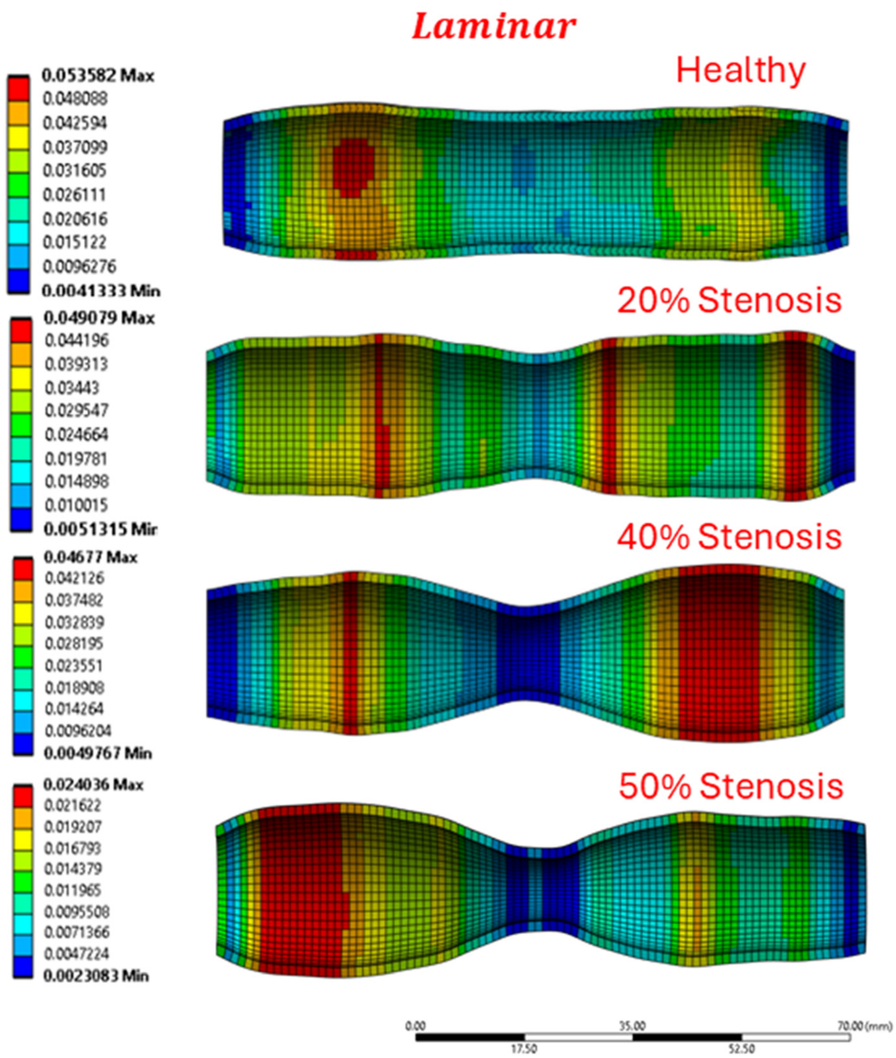

Fig. 5 The strain energy for the healthy and three stenoses (20%, 40%, and 50%) for laminar model

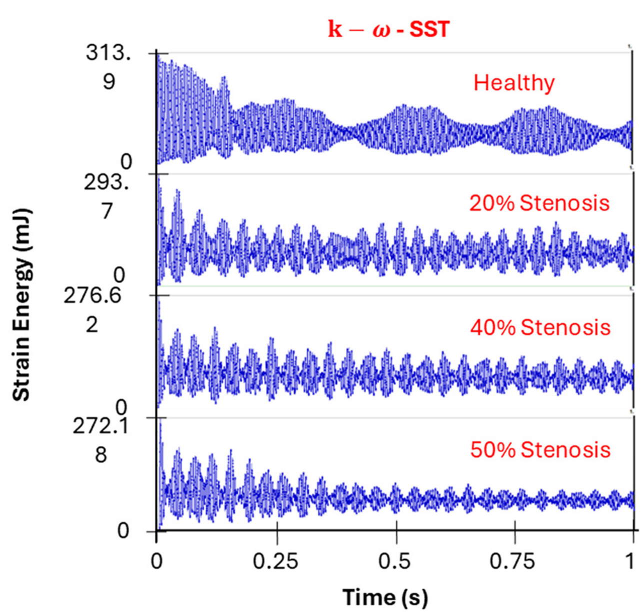

Fig. 6 The strain energy (mJ) for *k*–omega SST model

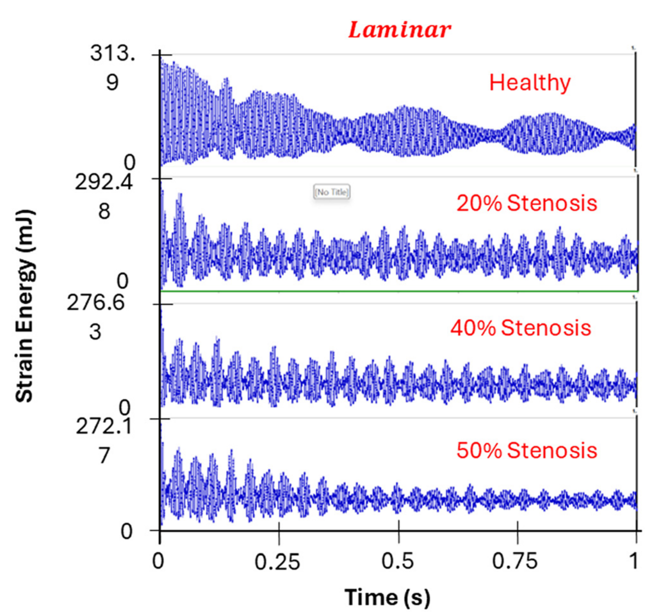

Fig. 7 The strain energy (mJ) for laminar model

k–omega SST and laminar, assuming the blood has Newtonian properties.

4 Conclusion

Understanding the relationship between the strain energy contours at the fluid-structure interface and the development of stenosis will assist in understanding the biomechanical behavior of the arterial pathology to diagnose stenosis early. The comparison between the *k*–omega SST and laminar models using Newtonian blood properties shows identical results for the strain energy under the one-way FSI method. The strain energy contours at the stenosis location show very low values compared to the healthy condition. This paper shows that in the investigation of healthy compared to stenosed artery development with (20–50% stenosis) based on clinical boundary conditions such as blood flow and pressure waveforms, the *k*–omega SST model outperforms the laminar model for short arterial segments and under the Newtonian assumption with a no-slip boundary wall and turbulent flow.

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Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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