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Evaluation of the Effects of Anastomosis Angle on the Performance of an Optimized Spiral Flow-Inducing Graft Design using CFD

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ABSTRACT

Bypass grafting is a common medical intervention used for people suffering from atherosclerosis, but the prevalence of graft failure due to disturbed hemodynamics necessitates the improvement of graft design for optimum blood flow. Spiral flow has been proposed as a mechanism to improve hemodynamics in grafts. A previous study optimized a spiral flow-inducing graft design, but it did not consider the effects of anastomosis angle despite its significant effects on blood flow. The purpose of this research is to further enhance the performance and patency of bypass grafts by determining how the anastomosis angle affects the hemodynamics of a spiral flow-inducing graft design using computational fluid dynamics (CFD). Distal anastomoses of 6 mm ridged graft and femoral artery constructs at varying anastomosis angles of 15° increments were analysed using steady-state CFD analysis under the assumptions of laminar, isothermal, stationary, rigid, non-Newtonian, and incompressible flow to determine the anastomosis angle that would yield optimum flow parameters. A 30° anastomosis angle was found to yield the most favourable flow conditions, particularly by minimizing recirculation one millimetre and five millimetres away from the toe (0.26% and 0% of the cross-sectional area of the artery, respectively) and pressure drop (474.8 Pa), as well as the complete elimination of areas affected by pathologically high wall shear stress (WSS). The findings of this study point out the potential benefits of a smaller anastomosis angle on the performance and patency of bypass grafts through the minimization of pressure drop and areas affected by recirculation and abnormally high WSS.

1. Introduction

In 2017, cardiovascular diseases (CVDs) led the list of the top causes of death globally with an estimate of 17.8 million deaths from the World Health Organization (WHO) [1]. Atherosclerosis, a condition where a buildup of plaque narrows or completely occludes the arterial lumen, is one of the most common types of CVD. Clogged arteries result in less blood flow into an organ or tissue. This translates to reduced oxygen supply to affected tissues or organs, otherwise known as ischemia,

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which may lead to several other cardiovascular conditions such as angina or myocardial infarction [2,3]. Vascular grafting is a common medical intervention performed to restore blood flow conditions. Autologous vessels are the current standard material used in grafts, but they have low availability and prominent failure rates [2].

Synthetic grafts are used as an alternative to autologous grafts. Currently, grafts made from materials such as polyethylene terephthalate (PET) or expanded polytetrafluoroethylene (ePTFE) are available commercially. However, they have limited clinical effectiveness and are characterized by high failure rates, especially in small-diameter vascular grafts (less than 6mm diameter) [4-6]. One complication encountered with the use of synthetic grafts is intimal hyperplasia (IH), the abnormal thickening of the neointima or pseudointima, at anastomosis sites between the host artery and graft which causes stenosis [7]. The development of IH is widely believed to be heavily influenced by hemodynamic parameters within the graft. In particular, wall shear stress (WSS) is one of the most widely utilized metrics in analyzing the relationship between blood flow dynamics and vascular pathology [8,9]. Since flow parameters are a function of graft geometry, it is therefore critical to design the optimum geometry that will result in favorable flow conditions in vascular grafts.

Computational fluid dynamics is a useful tool that can be used for non-invasive and inexpensive evaluation of graft design. It allows the quantification of hemodynamic factors in the graft and the prediction of the patency and performance of different graft designs [10-13]. Different graft designs have been evaluated using CFD. Some graft design parameters that have been looked into using CFD include the anastomosis angle [14-16], graft diameter [16,17], and the use of cuffs [18,19], among others. In a study by Ruiz-Soler *et al.,* [20] they used CFD to assess the use of ridges in graft design to improve hemodynamics within the graft. They suggested that a ridge induces spiral blood flow in the graft which may improve graft patency rates and longevity. Spiral flow is believed to remove unfavorable flow conditions such as stagnation, turbulence, and oscillatory shear stress which are believed to cause IH. However, their design is optimized only for a specific anastomosis angle (60°). The attachment angle between the graft and the native blood vessel heavily impacts the flow field, particularly in the vicinity of the attachment site. As such, the optimization of the anastomosis angle can potentially improve the performance and prolong the patency of grafts [21].

Previous studies on ridged graft design used constant anastomosis angle in their methodology even though an optimized anastomosis angle can potentially enhance graft performance. To the knowledge of the researcher, this is the first study to analyze the effects of anastomosis angle on an optimized ridged graft design. In the larger context, this can help improve graft design by extending their longevity and preventing failure which ultimately benefits people that suffer from or are at risk of developing CVDs due to atherosclerosis. The purpose of this research is to further enhance the performance and patency of spiral flow-inducing bypass grafts. To do so, the objective of the study was to determine how the anastomosis angle affects the hemodynamics of a spiral flow-inducing graft design using computational fluid dynamics (CFD).

2. Methodology

2.1 Geometric Models

Geometric models for the graft-artery constructs were created using Autodesk Fusion 360. For the study, end-to-side (ETS) distal graft anastomoses between the graft and host artery were generated. The internal diameters of the graft and the host artery were both set to 6 mm. The hemodynamic parameters were obtained and analyzed according to different anastomosis angles.

The cross-section of the graft was kept constant and was based on a previous study where the graft performance was optimized based on different geometric properties [20]. In this design, the ridge was semi-elliptical in shape with an area of 3.157 mm^2. The height of the ridge was 0.3 times the diameter of the graft. The trailing edge orientation was oriented at 180° (See Figure 1a). The grafts were attached to the host arteries using angles of 15° increments starting from 30° to 75°. The graft length was kept constant across all anastomosis angles. Sufficient lengths were added upstream and downstream of the graft length to ensure fully developed flow conditions into and out of the graft and the anastomosis junction (See Figure 1b).

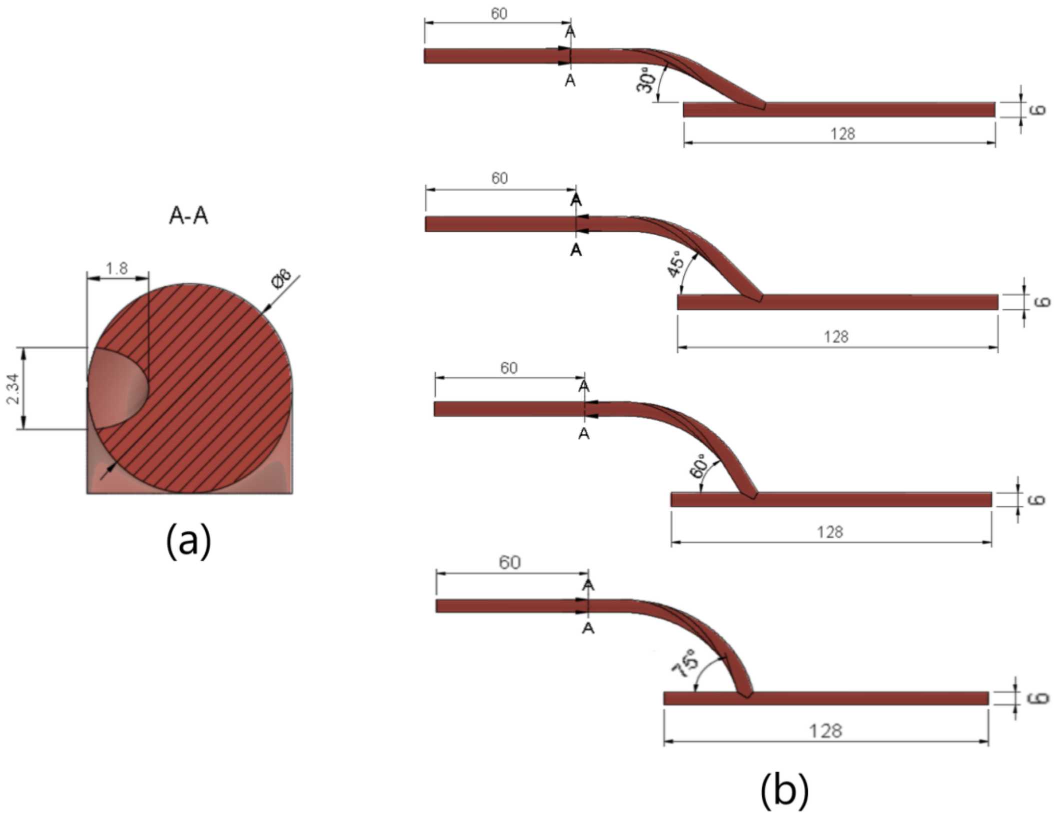

Fig. 1. (a) Cross-sectional profile of the graft in sections A-A; (b) Models with varying anastomosis angles

Figure 2 shows an isometric view of a sample model.

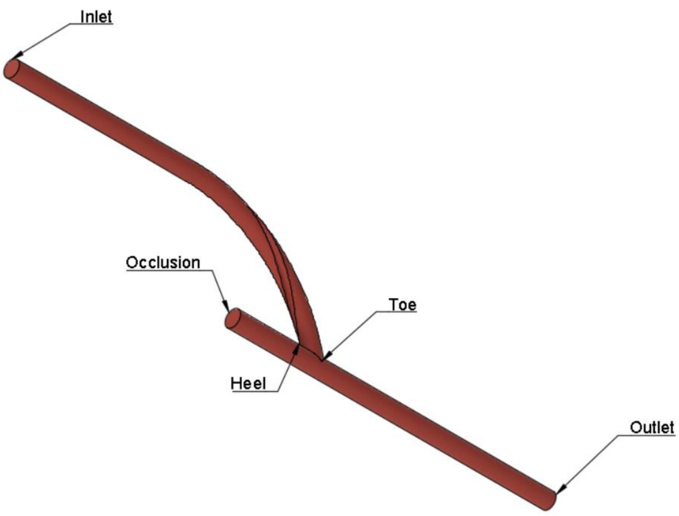

Fig. 2. Isometric view of the geometric model

2.2 Steady-State CFD analysis

To determine the optimum anastomosis angle, the researchers performed a steady-state CFD analysis. To begin with, a hybrid mesh was created using ANSYS-Meshing. The mesh consisted of fine prismatic near-wall elements and tetrahedral core elements. The orthogonal quality of the mesh was checked to be greater than 0.10 to ensure good quality. Due to the limitations of the license, the number of cells/nodes was limited to at most 512,000.

The flow physics was set under assumptions of laminar, stationary, and isothermal flow. Blood was described as an incompressible fluid with a density of 1050 kg/m^3. The non-Newtonian behavior of the blood was implemented using the Carreau model to represent the shear-thinning properties of blood [22]. For the inlet, a constant and uniform velocity of 0.317 m/s was set while a zero-pressure boundary condition was set at the outlet. In addition, rigid and no-slip boundary conditions were applied to the graft and artery walls [20].

To solve the governing equations of fluid dynamics, the finite-volume method using ANSYS-Fluent 2022 R1 Student Version was used. The convergence threshold was set to 10^{-6}. To further ensure convergence, the overall balances were monitored, along with the maximum value of the velocity at the outlet. The best anastomosis angle was decided by comparing values of WSS, retrograde flow, secondary velocity, and pressure drop. In particular, the flow was deemed to be enhanced with increased magnitudes of WSS and secondary velocity, and reduced pressure drop and recirculation [20].

3. Results
3.1 Pressure Drop

The constructal law of design states that fluid flow systems, such as the human vasculature, evolve to promote fluid flow and reduce resistance. This reduces the minimum pumping power needed to enable flow [23]. In the context of the cardiovascular system, reduced pumping power is desired to lessen the work exerted by the heart to circulate blood throughout the body. Pumping power is a function of the pressure difference between two points along the path. The total pressure is the sum of static, hydrostatic, and dynamic pressures [24]. The difference between the total pressure between two points is the sum of friction, static, and acceleration pressure drops [25,26]. As such, a graft design that minimizes total pressure drop must be sought.

Table 1 shows the total pressure drop between the inlet and outlet of the distal anastomosis constructs across varying anastomosis angles. The data suggest that the total pressure drop decreased with the anastomosis angle, dropping by about 5-6% in value per 15° anastomosis angle decrement.

Table 1
Total pressure drops according to anastomosis angle

Angle (Degrees)	Total Pressure Drop (Pa)
30	474.8
45	498.39
60	526.22
75	554.61

Several studies have also reported reduced pressure drop as a result of decreasing the anastomosis angle. Totorean *et al.,* [27] noted that for a fully occluded artery, smaller distal anastomosis angles had lower values of pressure drop throughout the cardiac cycle. In an optimization study using the constructal design method for a steady-state system, Dutra *et al.,* [28] showed that decreasing the anastomosis angle had a beneficial effect on grafts by reducing resistance to flow. Impiombato *et al.,* [29] also reported the same findings, using the same constructal design method but for pulsatile flow.

3.2 Wall Shear Stress

WSS is an important metric for the prediction of graft performance. It is a measure of the force exerted by a fluid in motion to a solid boundary and vice versa. It has been established in the literature that WSS is essential in maintaining endothelial homeostasis. As such, it is believed that WSS may be an important indicator of the development and/or progression of cardiovascular diseases [30].

There are two opposing claims about the optimal WSS to improve the efficiency of bypass grafts. One of these claims suggests that higher WSS is beneficial to graft design as it can prevent the development of intimal thickening and plaque formation. Low WSS is believed to prevent the activation of nitric oxide (NO) signaling pathways. NO signaling pathways prevent the progression of IH by inhibiting the proliferation of SMCs [31]. In addition, low WSS is linked to increased low-density lipoprotein deposition, macrophage migration, and increased adhesion molecules, all of which contribute to the development of atherosclerosis [32]. As such, some studies claim that higher WSS improves the efficiency of grafts.

Meanwhile, other studies suggest that high WSS is detrimental to the function of bypass grafts. High WSS is linked to increased thrombosis, lesion formation, and also to intimal thickening. Higher shear stress is observed to cause early graft failure due to thrombus formation, believed to be caused by platelet activation at higher WSS values [33,34]. Direct endothelial injury due to elevated WSS is believed to cause the formation of lesions [35]. Furthermore, high WSS, like low WSS, has also been linked to intimal thickening, possibly due to increased synthesis of vascular endothelial growth factors [36].

The debate between the benefits of low and high WSS in grafts makes it difficult to find a truly optimum graft design based on this metric. However, both hypotheses point out that extreme WSS values are detrimental to graft performance. As such, instead of minimizing or maximizing WSS in grafts, aiming for values that are closer to the natural physiologic conditions may be a safer and more beneficial approach. Data from the literature suggest that physiological WSS ranges from 0.1 Pa to 7 Pa [27,37]. Values beyond this range are referred to as pathologically low or pathologically high in this text.

Table 2 presents the WSS values in the artery obtained using CFD on ridged graft design with varying anastomosis angles.

Table 2
Wall shear stress according to anastomosis angle. Pathologically low WSS values are those lower than 0.1 Pa. Pathologically high WSS values are higher than 7 Pa

Angle (Degrees)	Maximum (Pa)	Area Average (Pa)	Area of Pathologically Low WSS (mm^2)	Area of Pathologically High WSS (mm^2)
30	5.98	1.88	430.18	0
45	7.37	1.98	444.81	3.33
60	10.18	2.09	435.69	49.41
75	13.37	2.16	421.54	83.01

In support of this, Figure 3 is a contour map showing the areas affected by abnormal WSS. The effect of anastomosis angle on reducing areas affected by pathologically low WSS may not be significant. First of all, the percentage difference between the biggest and smallest areas affected by pathologically low WSS stood only at 5.3%. This means that there was not much of an improvement in whichever angle was used to reduce areas affected by pathologically low shear. Furthermore, looking at Figure 3, the areas affected by abnormally low WSS were upstream of the graft outlet. There was no blood expected to flow into these areas anyway, so any improvements based on these areas would be of little use for enhancing graft performance.

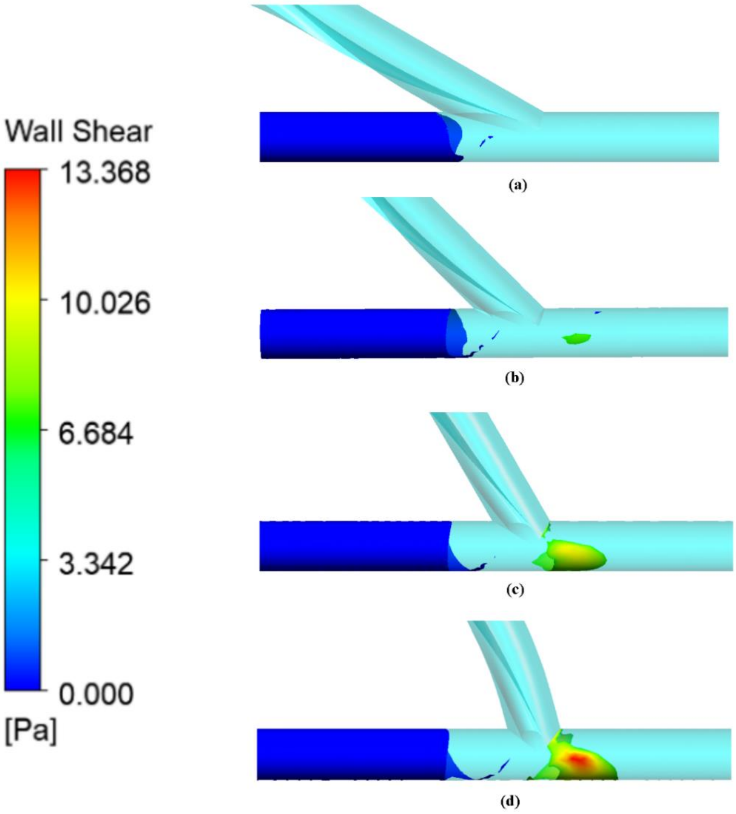

Fig. 3. Areas affected by pathologically low and pathologically high WSS values. (a) 30°; (b) 45°; (c) 60°; (d) 75°

The role of the anastomosis angle in optimizing graft performance was much more pronounced when observing areas affected by pathologically high WSS. When the anastomosis angle increased, a stark increase in areas of abnormally high WSS was observable, particularly in regions of the artery bed that directly impinged blood flow from the graft outlet. At 30°, no area of pathologically high WSS was detected. Interestingly, even at 45°, the problematic area was already minimal, showing the potential of small anastomosis angles in reducing the tendency of the graft to cause thrombosis and endothelial damage.

3.3 Recirculation

Recirculation is a phenomenon that is associated with the development of CVDs. It can cause increased stasis in blood vessels which allows materials in the blood to easily accumulate within the recirculation region and induce stenosis. It is also linked to IH, thrombosis, endothelial dysfunction, and atheroma formation [38,39]. Sunamura *et al.,* [40] observed that intimal thickening in bypass-grafted arteries was observed in regions affected by recirculation. They associate this phenomenon with the very low WSS found in these areas. Reininger *et al.,* [41] had shown that the presence of recirculation, despite an intact endothelial layer, promotes enough fibrin adhesion to obstruct the vessel lumen. It was suggested that recirculation zones characterized by low WSS are prone to atherosclerotic lesions and increased cholesterol deposition, initiating atheroma growth [42]. As such, an efficient graft must eliminate or at least reduce the presence of recirculation.

Table 3 shows the percentage of the cross-sectional area of the artery that is affected by recirculation – that is, negative axial velocity. These values were extracted 1 mm and 5 mm from the distal anastomosis toe.

Table 3
Percentage of the area affected by recirculation in the cross-section of the artery according to the anastomosis angle

Angle (Degrees)	Area affected 1 mm from toe (%)	Area affected 5 mm from toe (%)
30	0.26	0.00
45	3.17	0.00
60	5.21	1.00
75	6.58	1.61

The accompanying Figure 4 illustrates where recirculation is observed.

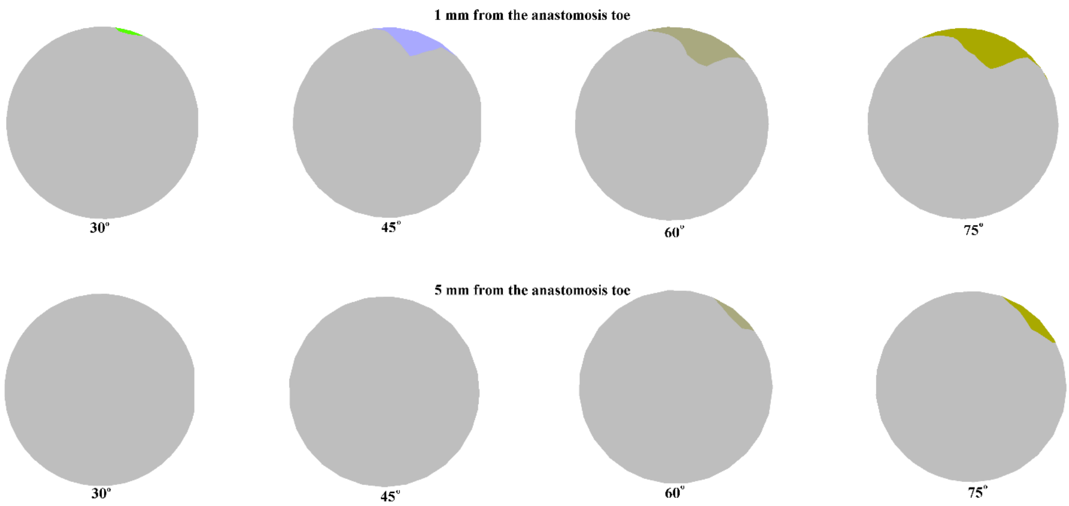

Fig. 4. Areas affected by recirculation according to anastomosis angles. Values were extracted from the artery at 1 mm and 5 mm from the anastomosis toe

It is clear that the degree of recirculation was positively related to the anastomosis angle. As the anastomosis angle increased, the area affected by recirculation in the upper part of the artery became larger. This was consistent on two monitoring planes along the artery. Of note is the recirculation five millimeters away from the anastomosis toe. At lower anastomosis angles, it can be seen that no trace of recirculation was observed in the artery, suggesting the possible benefit of a smaller anastomosis angle in bypass graft design.

The characteristics of recirculation zones according to anastomosis angle have been documented in several studies. Liu *et al.,* [16] aimed to determine the effects of anastomosis angle on the flow field of a distal ETS anastomosis. Similar to the results obtained in the present study, they observed a recirculation zone on the upper region of the artery near the anastomosis toe whose size increased with the anastomosis angle. The same results were seen in the *in vitro* study by Keynton *et al.,* [43] and *in vivo* study by Staalsen, further showing the absence of recirculation at the toe region in smaller anastomosis angles [44].

3.4 Secondary Velocity

Secondary velocity is the resultant of the radial and tangential components of the velocity vector. It, therefore, describes the swirling character of the flow. Table 4 shows the maximum and area average values of secondary velocity 50 mm from the anastomosis toe. Among the models evaluated, the 60° anastomosis angle yielded the highest secondary velocity. Meanwhile, the 30°-angled graft recorded the lowest maximum and area average values for secondary velocity.

Table 4
Secondary velocity according to anastomosis angle. Values were obtained 50 mm from the distal anastomosis toe

Angle (Degrees)	Maximum (m/s)	Area Average (m/s)
30	0.039	0.018
45	0.051	0.021
60	0.059	0.024
75	0.055	0.021

The swirling motion is illustrated by the secondary velocity contours and streamlines shown in Figure 5. It is evident that the internal ridge successfully induced spiral flow in the target artery. For each of the 45°, 60°, and 75° grafts, a single dominant spiral was observed. This resembled the optimal flow pattern observed by Ruiz-Soler *et al.,* [20] when they oriented the ridge at 180°. They hypothesized that this orientation results in less suppression by the arterial walls upon the impingement of flow on the artery bed.

Meanwhile, for the 30° graft, the swirl was characterized by two concentric spirals. This concentric spiral flow may explain the pressure drop and WSS values observed for the 30° graft. Because some magnitude of secondary velocity was lost to the internal spiral flow, there was a less intense swirling motion on the external spiral flow. Hence, less shear stress and friction were generated on the arterial wall, causing lower WSS and pressure drop values observed for the 30° graft compared to others [45].

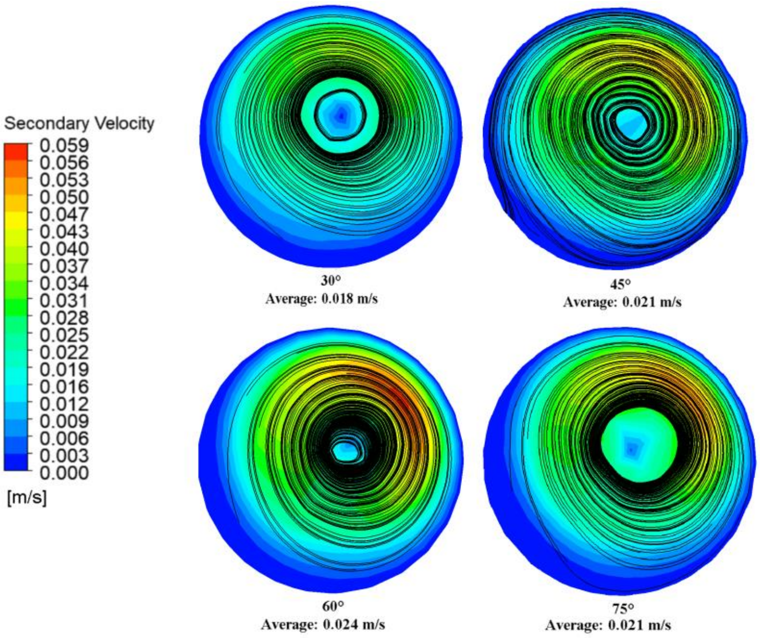

Fig. 5. Secondary velocity contours and crossflow streamlines according to anastomosis angle. (a) 30°; (b) 45°; (c) 60°; (d) 75°

3.5 Optimum Angle

It is clear from the results shown previously that the anastomosis angle affects the hemodynamics in the distal anastomosis region of an ETS graft. As such, it can be used as a design criterion for the optimization of graft design. A good graft design must be able to minimize pressure drop, recirculation, and areas of pathological WSS. Furthermore, due to the observed benefits of spiral motion in graft performance, an increased swirling character can be sought. Secondary velocity, the resultant of tangential and radial components of the velocity vector, may be used to characterize this.

Figure 6 presents a spider chart used to compare and summarize the design criteria used by the researcher to optimize the flow in spiral flow-inducing graft design. All values were normalized to the values obtained for the 60° graft. Smaller values were preferred for the pressure drop, areas of pathological WSS, and recirculation. Meanwhile, since increased secondary velocity was sought, its reciprocal value was calculated such that larger secondary velocity values were projected farther from the center. Therefore, the graft occupying the greatest area in the spider chart had the best performance among the models being studied.

Evidently, the 30° graft has the greatest area in the chart. In particular, it outperformed the other graft designs in three areas. It significantly reduced the areas affected by recirculation and pathologically high WSS. It also slightly reduced the pressure drop across the length of the geometric model. In all these three criteria, there was a clear negative relationship between the performance of the graft and the anastomosis angle.

On the other hand, the 30° graft was outperformed by the 60° graft in reducing the areas affected by pathologically low WSS, but the difference was minuscule. In fact, the angle seemed to have no significant beneficial impact in reducing areas affected by pathologically low WSS. This was evidenced by the very small difference in values observed across different models and the fact that as shown in Figure 2, the areas affected by pathologically low WSS only resided in the bypassed region anyway.

Moreover, the 30° graft performed the worst in terms of the secondary velocity or the spiral character of flow. The 60° graft outperformed the other models, indicating that the design of Ruiz-Soler *et al.,* [20] may have been specifically optimized with the spiral flow characteristics as the main criterion. However, by itself, secondary velocity is not a direct indicator of graft performance. In literature, it is only expected to improve other values such as WSS. Therefore, even if the 30° graft performed the worst in increasing the secondary velocity, it does not necessarily mean that it resulted in detrimental biological effects. The larger secondary velocity observed in the 60° graft may have been actually detrimental to its biological impact by increasing the pressure drop and areas affected by pathologically high WSS.

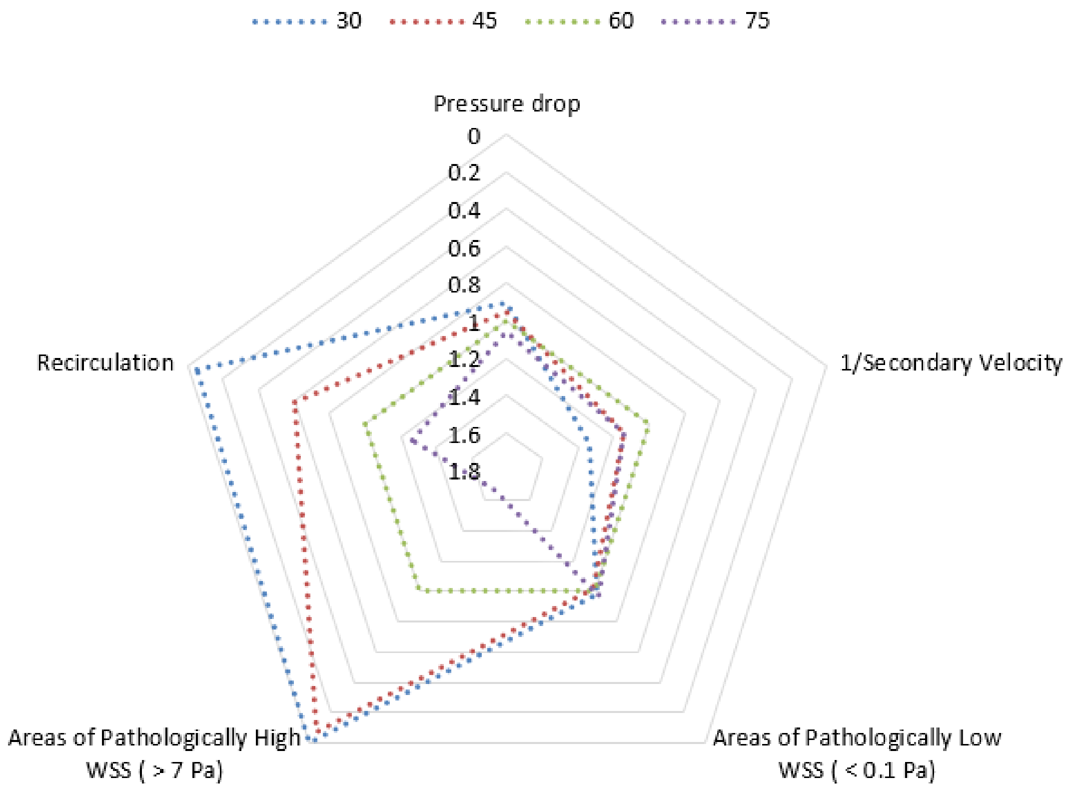

Fig. 6. Comparison of pressure drop, secondary velocity, areas of pathologically low and high WSS, and recirculation across different anastomosis angles

In short, the 30° graft was expected to enhance the performance of an optimized spiral flow-inducing graft design. Judging from three out of the five criteria compared, decreasing the angle seemed to have made a positive impact on graft performance. This is corroborated by other studies in the literature which hypothesized that smaller anastomosis angles are beneficial to graft hemodynamics due to less "disturbed flow". Studies reported the reduction of abnormal flow characteristics such as WSS peaks and gradients, flow separation, recirculation area, and secondary flow components with smaller anastomosis angles, confirming the findings in this study [42,46].

4. Conclusions

This paper aimed to evaluate the effects of anastomosis angle on the performance of an optimized design of a spiral flow-inducing graft to determine the angle that would yield the optimum flow parameters. Through CFD, it was found that smaller anastomosis angles could further enhance the performance of a ridged graft design through the minimization of pressure drop, recirculation, and areas affected by pathologically high WSS. The findings of this study contribute to the body of literature aiming to improve graft performance by showing how smaller anastomosis angles could enhance the hemodynamics of spiral flow-inducing graft design.

Several simplifying assumptions were used to reduce the complexity and computational cost of solving the problem. The geometries used for the study were idealized. In actuality, grafts and arteries are irregularly shaped. Future studies may incorporate imperfections in these geometries or use actual imaging models to represent the objects more accurately. Also, the study only considered the distal anastomosis region. Future studies may look into the effects of the anastomosis angle and spiral flow on the proximal anastomosis region. In performing the simulations, the walls were assumed to be rigid. Hence, the material aspect of the design was ignored even though the deformation of blood vessels affects hemodynamics and vice versa. As such, future iterations of the study could use fluid-structure interaction (FSI) simulation to capture more realistic results. Concerning this, because the material aspect was not considered, the biomaterial aspect of the design was also ignored. Future researchers may also take it into account.

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