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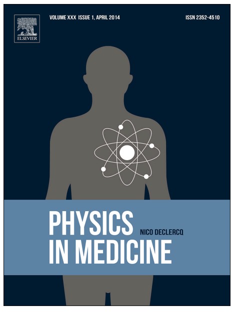

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Suction Force-Suction Distance Relation during Aspiration Thrombectomy for Ischemic Stroke: a Computational Fluid Dynamics Study

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Abstract

Acute Ischemic Stroke (AIS) is the major type of stroke occurring in patients. Aspiration thrombectomy, which uses suction to remove the thrombosis, is a promising technique in the clinical treatment of AIS patients. In this research a computational fluid dynamics (CFD) analysis was conducted to model the blood flow dynamics in a simplified cerebral model during an aspiration thrombectomy procedure. The flow system being analysed was a typical in vitro cerebral flow model, and the system parameters were set based on the clinical and in vitro data reported in open literature. The simulated flow field features showed good correlation with the in vitro response as reported in literature. The CFD study provides detailed technical data including the peak velocity occurring at the catheter tip and the suction force-suction distance relation during the aspiration thrombectomy procedure, which are useful new knowledge and have the potential to influence future catheter design as well as clinical operational protocols used during thrombectomy intervention.

Keywords

Acute Ischemic Stroke, Aspiration Thrombectomy, Computational Fluid Dynamics, Suction Force, Suction Distance

Nomenclature

D	Diameter
f	frictional force
F	Force
L	Suction distance, i.e., the distance between the catheter tip and the proximal surface of the thrombus
P	Pressure
S	Suction force, i.e., summation of all the pressure forces acting on the proximal and the distal surfaces of the thrombus

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Subscripts

cc surface contact action between the catheter tip and the thrombus surface

pc pressure action on the surface of the thrombus (due to catheter suction)

pd pressure action on the distal surface of the thrombus

pp pressure action on the proximal surface of the thrombus

pv pressure action on the surface of the thrombus (due to the vascular intra-luminal pressure)

w wall action

1. Introduction

Stroke is the third most common cause of death worldwide and the number of people suffering a stroke annually has increased in the last twenty years resulting in a significant increase in stroke-related deaths and disabilities ([1]). Ischemic stroke accounts for about 80% of all stroke cases and occurs when one or more arteries that supply blood to the brain are occluded by a thrombus. Good recovery and improved outcomes in ischemic stroke patients are highly dependent on the time taken to restore blood flow to the brain ([2]). The most widely used approach to restore blood flow rapidly is a technique called thrombolysis which uses enzymes to break up the clot. However, recanalization rates with intravenous thrombolysis are poor in patients with occlusion of large intra-cerebral arteries such as in the basilar artery or proximal middle cerebral artery ([3]).

An alternative, endovascular treatment, is associated with considerably higher recanalization rates than intravenous thrombolysis ([2]). The most commonly used methods for endovascular treatment are mechanical thrombectomy (using a mechanical retrieval device to grab and remove the thrombus) and aspiration thrombectomy (using a pump or syringe with high negative pressure to suck and remove the thrombus). Aspiration thrombectomy achieves consistently higher recanalization rates than the mechanical thrombectomy, but clinical outcomes with aspiration thrombectomy are variable ([4]), with very poor recovery

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rates in four studies ([5-8]) and good outcomes in others ([9-12]). However, a recent prospective study has reported improved clinical outcomes using a large bore aspiration catheter ([13]) and there are compelling reasons to use aspiration thrombectomy for clot removal over mechanical thrombectomy including efficiency and cost effectiveness. This is reflected in the appearance of new aspiration devices that claim to have design features that improve aspiration efficiency. However, little is known of the interaction between aspiration devices and clots or of flow conditions within the brain and these factors have significant influence on the aspiration efficiency. Another factor is the variability between interventionists in the use of aspiration devices in the clinical setting. Therefore increasing our understanding of thrombus-device interaction and flow conditions in the cerebral circulation will help to improve device designs and operational techniques ([14]).

The aspiration thrombectomy technique is still in its infancy and needs substantial improvement before it can be accepted as a routine treatment procedure. For example, it is still not clear what are the optimal levels of suction pressure and pick-up force that should be applied to remove thrombi of different sizes, different stiffness, and in different cerebral vessels; what is the exact relation between the suction force produced on the thrombus and the suction distance (i.e., the distance from the suction catheter tip to the thrombus). This information is important as it will directly influence the operational protocols of the aspiration thrombectomy procedure. Different views are held about the optimal choice of the suction distance in order to achieve the maximal suction force. Tunuci et al ([15]) maintained their catheter tip 3-5mm away from the proximal side of the clot during aspiration in order to achieve the maximal suction; Pearce et al ([16]) used 3mm suction distance instead, while most other researchers ([11, 14, 17, 18]) preferred to fully engage the catheter tip onto the thrombus surface in order to produce the maximal suction. It is hard to judge which one is the best choice until an in-depth study is conducted into the suction force-suction distance (S-L) relation.

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The detailed flow condition in the aspiration thrombectomy procedure is influenced by multiple factors, including the distorted flow profile due to the irregular geometry of the brain vessels, nonlinear contact and frictional forces between the thrombus and the vessel wall, and the suction action produced by the aspiration intervention. To study this complex response process, researchers have built mechanical fluid flow systems as simplified representations of the cerebral flow loop, and conducted in vitro tests to observe the flow features around the blood clots during different mechanical thrombectomy procedures ([14-16]). These in vitro studies helped to reveal the catheter-thrombus interaction features to some degree. However, with the simplified mechanical representation and the restriction of the small vessel geometry only discrete pressure/flow signals can be collected at selected locations, and video images recorded to provide a rough description of the overall flow picture. The data and images recorded in this manner are insufficient for the evaluation of the suction force in the aspiration procedure, while suction force is an important parameter as it is a more direct and descriptive way of predicting the outcome of aspiration intervention.

Computer modelling is a mature research tool that has been widely applied in the study of engineering and biomedical applications. Specifically in the area of cerebral blood flow modelling, computational fluid dynamics (CFD) is one of the major techniques being used by researchers to simulate the complex blood flow responses in different healthy and diseased conditions ([19-23]). However, published CFD studies of aspiration techniques and cerebral flow are scarce, with only one recent study reporting a simple CFD analysis used in conjunction with an in vitro study on a mechanical model ([14]).

This study focused on the CFD modelling of the flow features in the middle cerebral artery during the aspiration thrombectomy procedure. For comparison with previous in vitro data, this study used the flow domain similar to that in the mechanical system built by Lally et al ([14]). The initial CFD data for the two cases (with and without thrombus) in the vessel were compared with the results of Lally et al for qualitative validation. Following this, CFD analysis was extended to reveal the S-L relation in the aspiration thrombectomy.

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2. **Methods**

This study analysed the fluid flow response during aspiration intervention in an in vitro test rig. The general configuration of the test rig was the same as that used in the study of Lally et al ([14]). Also the system operating conditions such as the pressure head applied to the flow loop were kept consistent. However, to facilitate model construction and to reflect more general situations, some geometrical details, e.g. minor variation of cylindricity and minor bending at the two ends of the glass tube as the vessel model, small round corners at the tip of the catheter etc., which were difficult to quantify, were neglected in the current study.

2.1 CFD analysis

In conducting the CFD analysis, the fluid was considered to be incompressible and Newtonian, with a density of $1300kg/m^3$ and a dynamic viscosity of $3.2cP$, to match the properties of the real blood ([24]). The elasticity of the vessel wall and that of the catheter wall were neglected. Thus the system dynamics are governed by the Navier-Stokes equation and the mass conservation equation. The aspiration intervention causes strongly disturbed vortex flow near the catheter tip, and the shear stress transportation model [25] was used to calculate the turbulence flow effect. Detailed flow domain geometry and the boundary condition settings were explained in the following sections that describe the simulation cases.

Ansys CFX version 17.0 running on a HP Z210 workstation (which has 4 CPUs and 8Gb memory) was used to conduct the CFD analysis. The CFD calculation was considered as a steady simulation, with the convergence criterion chosen as the root mean squares of the residuals for the flow variables (including the pressure *P* and the three dimensional velocity components *u*, *v*, and *w*) being below 10 to the minus 5th power. The education license used had restrictions on the maximum scale of solvable problems, thus the maximum allowable mesh size has been used and no mesh independent test was conducted. This would influence the accuracy of the detailed values in the final solution but would not change the nature of the results which would be meaningful for this initial stage of study.

2.2 Qualitative evaluation of flow features near the catheter tip with and without thrombus presented

Based on the configuration of the test section in Lally et al.'s study ([14]), a simplified vessel geometry was adopted and the middle cerebral artery model was represented by a straight cylindrical tube. In this study the vessel inner diameter was set as 4mm and the vessel segment had an overall length of 60mm. A 4MAX catheter with diameters of 2.03mm outer and 1.04mm inner was to be inserted into the vessel from the proximal end of the vessel, and the depth of the catheter insertion was 57mm. For simplicity it was assumed that the catheter was aligned concentrically with the vessel.

Two cases were analysed: case 1 was for the situation without the thrombus in the vessel; case 2 was for the situation with the thrombus in the vessel, and the proximal surface of the thrombus was exactly at the middle section of the vessel along the length direction, as shown in Fig.1 (a) and (c). Fig.1 (b) and (d) show the corresponding flow field configuration used in the CFD calculations. Based on the configuration of Lally et al ([14]), in case 1 both the proximal and the distal ends of the vessel were subjected to $90mmHg\left(=12kPa\right)$ pressure, which was simulated by setting the pressure inlet condition in the CFD simulation. In case 2 the rigid thrombus served as a solid barrier that separates the proximal and distal part of the vessel, so only half of the flow domain was considered in the calculation. In this situation the proximal surface of the thrombus was considered as a non-slip solid wall in the calculation, while at the proximal end of the vessel (where the catheter was inserted) the same $90mmHg\left(=12kPa\right)$ was applied as the pressure inlet condition. In both cases 1 and 2, at the catheter outlet a static pressure of $-30kPa$ was applied as the pressure outlet condition. This suction pressure applied at the catheter outlet was chosen based on the clinical and in vitro test conditions used by previous researchers ([8, 15, 16, 26-28]). The inner wall of the vessel, the outer/inner wall of the catheter, and the catheter tip were all

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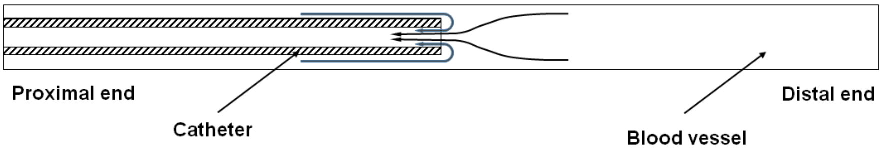
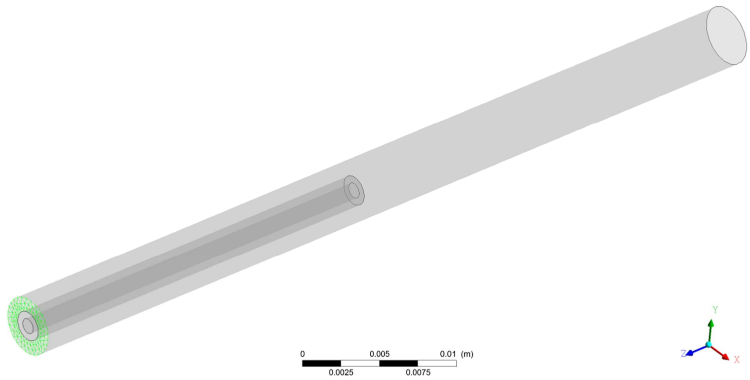
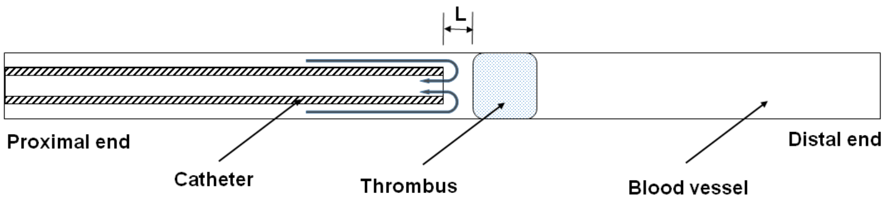
considered as non-slip walls. For case 2, the catheter tip was 3mm away from the proximal thrombus wall.



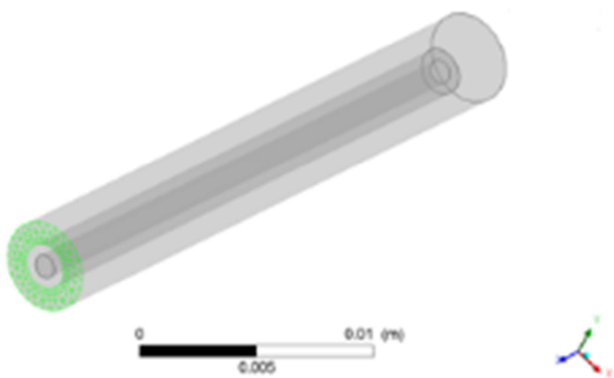
(a) Schematics of the flow field configuration without thrombus



(b) Domain geometry for the flow field without thrombus



(c) Schematics of the flow field configuration with thrombus



(d) Domain geometry of the flow field with thrombus

Fig. 1 Flow field configuration in the CFD study

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2.3 Study of the S-L relation

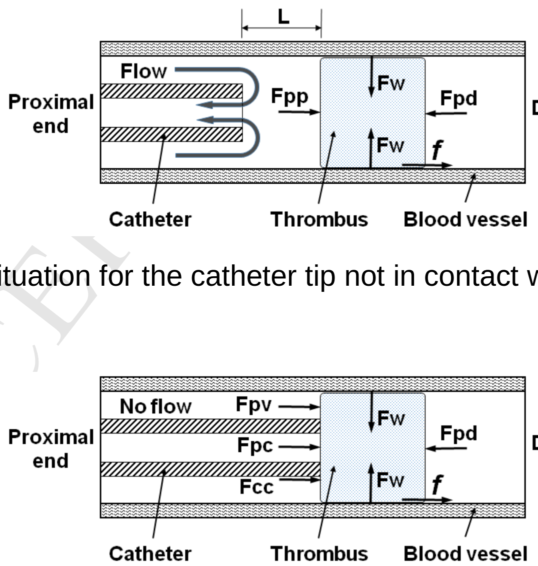
To understand the physical mechanism underlying the clinical aspiration operation, it is of primary importance to understand the forces acting on the thrombus and to find the S-L relationship during the procedure. Fig. 2 illustrates the forces acting on a thrombus when it is trapped in the cerebral vessel, with the gravitational force neglected because of its small scale. In the radial direction of the vessel, wall compression force was naturally balanced between any of the two compression forces along each diameter direction. In the axial direction of the vessel, there were two or three types of forces acting on the thrombus, depending on the contact condition between the thrombus and the catheter. When the catheter was not in contact with the thrombus, i.e., when the suction distance $L > 0$, there were fluid pressure forces F_{pp} and F_{pd} applied on the proximal and the distal surfaces of the thrombus (here the pressure force is defined as the product of the pressure times the sectional area, i.e, $F = P * A$, with the proximal side pressure to be decided through the CFD calculation, and the distal side pressure being $90mmHg\left(=12kPa\right)$ based on the in vitro data in ([14])), and the frictional force f existed on the lateral surface of the thrombus which was in contact with the vessel wall (here the frictional force is defined as the product of the frictional coefficient times the contact force, i.e, $f = c * F_w$),. The force balance on the thrombus in this situation is described by the equation:

$$\sum F = F_{pp} + f - F_{pd} = 0 \qquad (1)$$

When the catheter was in close contact with the thrombus, i.e., when the suction distance $L = 0$, there was no blood flow on both the proximal and the distal sides of the thrombus, and the thrombus experienced three types of forces: pressure force, friction force, and the contact force applied by the catheter tip. On the proximal surface, there was a pressure force F_{pv} applied by the proximal side blood static pressure on the ring area enclosed by the inner circumference of the vessel and the outer circumference of the catheter, another pressure force F_{pc} produced by the catheter suction pressure on a central circular area enclosed by the inner circumference of the catheter, and the contact force F_{cc} between the catheter tip and the thrombus (whose magnitude depends on the detailed contact condition). On the distal surface, there was a pressure force F_{pd} applied by the distal side blood static pressure on the whole distal surface. On the lateral surface of the thrombus in contact with the vessel wall, the friction force f still existed. The force balance on the thrombus in this situation is described by the equation:

$$\sum F = F_{pv} + F_{pc} + F_{cc} + f - F_{pd} = 0 \quad (2)$$

It should be noted that, to be accurate, there is no such a physical force called suction force existing in this situation, and the suction force S actually is the summation of all the pressure forces acting on the proximal and the distal surfaces of the thrombus ($S = F_{pp} - F_{pd}$ or $S = F_{pv} + F_{pc} - F_{pd}$ depending on the situation).



(a) Situation for the catheter tip not in contact with the thrombus

(b) Situation for the catheter tip in close contact with the thrombus

Fig. 2 Diagram of the forces acting on the thrombus during the aspiration operation

In analysing the S-L relation, a CFD simulation was conducted using the model configuration for the case with thrombus in the vessel, as described in Fig. 1 (c) and (d), with the suction distance changing in the range of $L = 0.1 \sim 5.0mm$. The boundary conditions were the same as used for the above calculation. The range of $L = 0.1 \sim 5.0mm$ was chosen to cover the suction distance values used in the previous experimental cases as presented in ([11, 14-18]) as well as to consider the realistic mesh size achievable in the CFD calculation. In this situation, the suction force is calculated as:

$$S = F_{pp} - F_{pd} = \left(P_{pp} - P_{pd}\right) \cdot \frac{\pi}{4} D^2 \qquad (3)$$

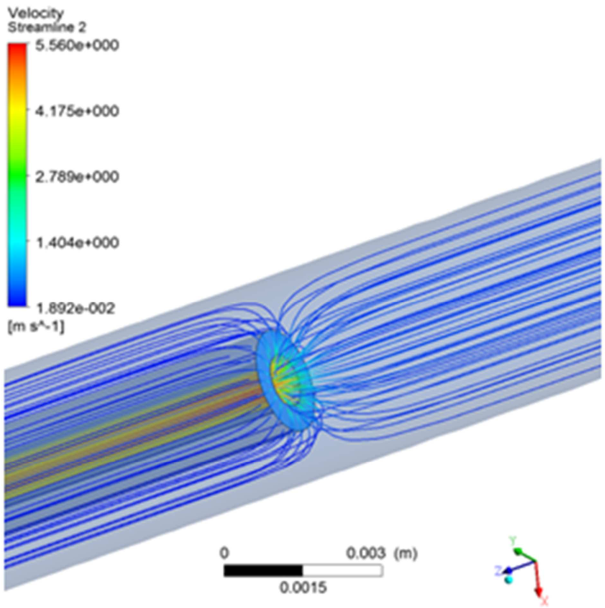
The design optimisation module in the ANSYS Workbench environment is a helpful tool in making the analysis procedure fully automatic. For this purpose, the suction distance L was assigned as the design input parameter, and equation (3) for the suction force was defined in the ANSYS CFX calculation results and assigned as the design output parameter. The CFD results were fed into the Ansys Response Surface Optimisation module for automatic repetition of the full procedure of geometry revision, mesh regeneration, and CFD recalculation under different L values. To have improved result accuracy, two optimisation cycles were implemented and the results were combined for final analysis: the first cycle with $L = 1.0 \sim 5.0mm$ to reveal the wider range of $S - L$ relation; and the second cycle with $L = 0.1 \sim 1.0mm$ to reveal the more precise $S - L$ relation when the catheter was about to be in contact with the thrombus. The default central composite design scheme for the design of experiment was adopted so each range covers five equidistance points. The results for the two cycles were then combined for formal analysis.

The extreme case of $L = 0mm$ as used by Lally et al ([14]) needs to be analysed using a pure static force balance case instead of using the CFD analysis, as in this situation there is no blood flow. The situation is described by Fig. 2(b) and equation (2) above. For this situation, the suction force is calculated as:

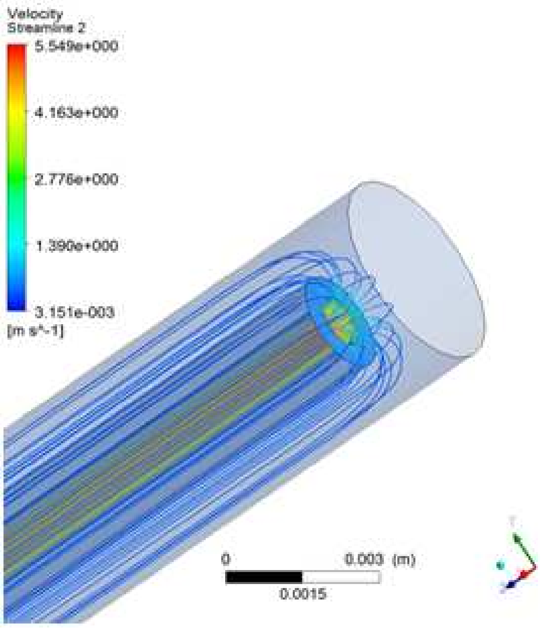
$$\begin{aligned} S &= F_{pv} + F_{pc} - F_{pd} \\ &= 12kPa \times \frac{\pi}{4} \times \left[(4mm)^2 - (2.03mm)^2\right] + (-30kPa) \times \frac{\pi}{4} \times (1.04mm)^2 - 12kPa \times \frac{\pi}{4} \times (4mm)^2 \qquad (4) \\ &= -0.0643N \end{aligned}$$

The negative sign denotes that the suction force is towards the direction of the catheter body.

3. Results



(a) Case without thrombus (Stream lines start from both the proximal and distal ends of the vessel, and merge at the catheter tip, then flow through the catheter inner channel. Flow from the proximal end makes a U turn at the catheter tip.)



(b) Case with thrombus (Stream lines start from the proximal end of the vessel, and distal end is blocked by the thrombus so is truncated. The cutting plane on the distal end represents the wall boundary formed by the thrombus. Flow from the proximal end makes a U turn at the catheter tip.)

Fig. 3 Stream lines of the flow field near the catheter tip

Based on the analysis technique presented above, CFD studies were conducted to analyse the blood flow dynamics in the simplified mock cerebral model. First the flow features near the catheter tip with and without thrombus present were evaluated, for qualitative comparison with the in vitro test data produced by Lally et al ([14]). Next the S-L relation was studied by varying the suction distance in the range of $L = 0.1 \sim 5mm$. In the following, the results are presented.

3.1 Qualitative evaluation of flow features near the catheter tip with/without thrombus presented

Fig. 3 (a) and (b) show the stream lines of the flow field for the situations with and without thrombus present in the vessel. For the case of flow without thrombus as shown in Fig. 3(a), it is observed that stream lines start from both the proximal and distal ends of the vessel, and they merge at the catheter tip, then flow through the catheter inner channel. CFD results suggest that the suction in the catheter produces a volumetric flow rate of $3.51 \times 10^{-6}\, m^3/s$ in the catheter inner channel, of which $6.7 \times 10^{-7}\, m^3/s$ (20%) comes from the proximal end, and $2.84 \times 10^{-6}\, m^3/s$ (80%) from the distal end. The distal side contributes 80% of the suction flow in the catheter. This is understandable because the distal side flow channel is wider than the proximal side one so that the resistance to the flow is less than that from the proximal side. It is observed that flow from the proximal end experiences a sudden change of direction at the catheter tip. Flows from both the proximal and the distal ends merge in the catheter, while the catheter has a much smaller inner diameter than the vessel. As a result, the flow velocity in the catheter inner channel is much higher than that outside of the catheter body. The highest velocities are located in the region immediately proximal to the catheter tip, with the magnitude of the peak velocity reaching $5.56 m/s$. The sudden change in the flow direction near the catheter tip combined with the peak velocity make the immediate inside region of the catheter tip the most critical area of flow changes, and this is also the area with elevated velocity gradient and thus shear stress. This will have adverse influence on the blood cells in this area but this is not a significant problem, since the blood cells under the influence will be extracted from the body through the catheter anyway.

Fig. 3(b) illustrates the stream lines of the flow field with thrombus presented at the middle of the vessel, and the catheter tip held $3mm$ away from the proximal surface of the thrombus. As described previously, the thrombus blocks the flow from the distal end, so the distal half of the vessel including the thrombus is truncated from the overall flow domain. As a result, there is no flow coming from the distal end of the vessel. Suction in the catheter produces a flow rate of $3.5\times10^{-6}\ m^3/s$ in the catheter inner channel, which equals the flow rate entering the domain from the proximal end of the vessel. Stream lines of the flow coming from the proximal end generally maintain the same shape as in the case without the thrombus present in the vessel. Also here the immediate inside region of the catheter tip is where the peak velocity occurs and the most critical area of flow changes in the flow domain. The peak velocity reaches a value of $5.55 m/s$, only slightly smaller than that for the case without thrombus. In addition the CFD simulation predicts that a suction force of $0.0057N$ towards the catheter proximal direction is produced on the thrombus surface, under the simulated conditions. The relation between the suction force and the suction distance is investigated in the following section.

3.2 S-L relation

For analysing the S-L relation, two cycles of parameter analysis were conducted in the ANSYS Workbench environment using the CFX software, and the results were combined to analyse the flow response over the full range of $L = 0.1 \sim 5.0mm$ and over the local range of $L = 0.1 \sim 1.0mm$ for the suction distance. The corresponding results are shown in Fig. 4 and Table 1.

Fig. 4(a) shows the S-L relation over the full range of L values, while Fig. 4(b) specifically magnifies the response for the local range of L values and compares the CFD results with the theoretically predicted suction force with the catheter tip in full contact with the thrombus surface. Table 1 lists the detailed S-L data obtained through CFD and theoretical

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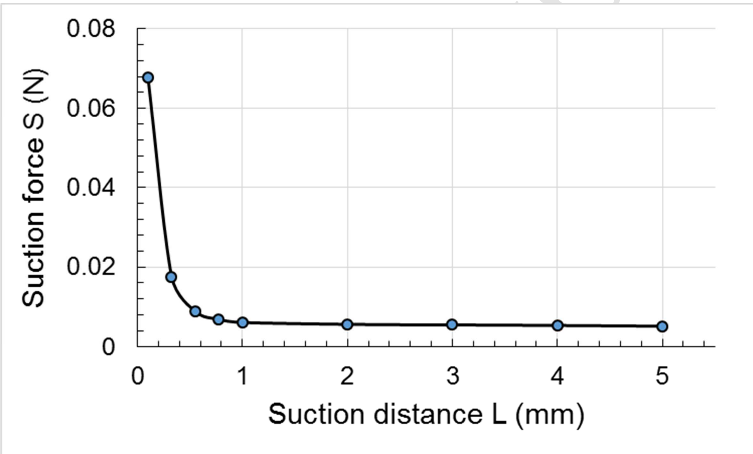
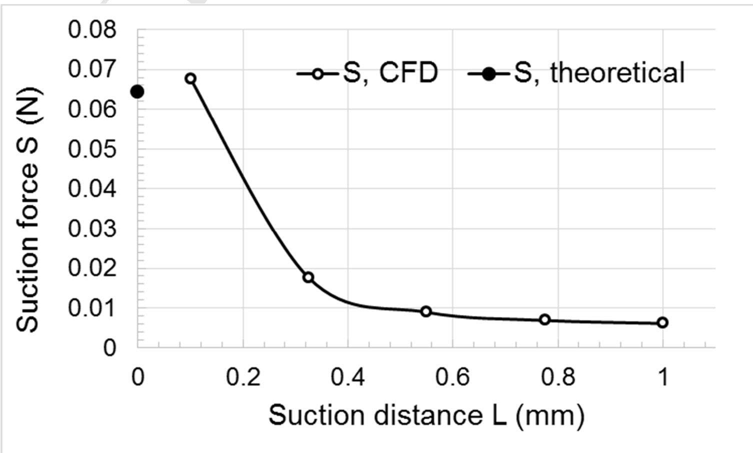
calculations. Generally the suction force S shows only minor increments when the suction distance L is reducing from $5.0mm$ to $1.0mm$. However, when L is further reduced from $1.0mm$ to $0.1mm$, S shows an exponentially increasing trend. When L is reduced to $0.1mm$, S is more than 10 times larger than that for the distance of $1.0mm$. A natural extrapolation from the CFD data may suggest that S will reach the peak value when the suction distance is reduced to zero, i.e., when the catheter tip is in full contact with the thrombus surface. However, by comparing the CFD data with the theoretical prediction calculated above, the suction force S for the full contact situation is actually slightly smaller than the one when leaving the suction distance at $0.1mm$. This interesting phenomenon needs to be investigated further in the next stage of study.



(a) Full range results based on CFD calculation



(b) Local range results, for comparison between CFD data and theoretical prediction

Fig. 4 Suction force-suction distance relation

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Table 1 Results of suction force-suction distance relation

Suction distance L (mm)	Theoretical prediction	CFD calculation results								
	0	0.1	0.325	0.55	0.775	1	2	3	4	5
Suction force S (N)	0.0643	0.0676	0.0176	0.0089	0.0069	0.0061	0.0057	0.0055	0.0054	0.0052

4. Discussion

In this research, a CFD study was conducted to analyse the typical fluid flow dynamics in the simplified cerebral model during the aspiration thrombectomy procedure. Although CFD has been extensively applied to analyse a wide range of cardiovascular flow problems and its validity has been fully tested, its usage in studying the blood flow response in mechanical interventions of vascular blockage is still very rare. The current study can be considered as a pioneering work to contribute to fill this knowledge gap.

Study of cerebral flow response is important as it provides useful knowledge and understanding to guide the clinical treatment of stroke patients. In the past decades, plenty of clinical research papers have been published to report various successful treatments using mechanical intervention techniques, with aspiration thrombectomy being the most vibrant among the different techniques reported. However, due to the nature of studies these publications all focused on describing the treatment procedure and the statistic results of treatment outcomes, with little or vague information being given about the detailed operational data such as the suction force, blood flow velocity etc. The present study was conducted in order to disclose those missing quantitative pieces of information about the blood flow response during treatment interventions. The preliminary CFD results obtained in this study not only reveal the general flow field features during the aspiration procedure, but also provide detailed technical data in the critical region near to the catheter tip, including the peak flow velocity developed near the catheter tip, and the S-L relationship during the aspiration process. The simulated general flow field features agree well with the ones reported by Lally et al ([14]) in their in vitro experimental study. Although Lally et al did not report all quantitative data for comparison with the current results, agreement of the general flow field features can serve as a first pass validation of the current CFD calculation study. On top of the general flow field features, the present study also yields velocity information of the blood flow and the useful S-L relation during the aspiration intervention, which need to be verified against clinical or in vitro data. It is disappointing that such information is missing from open literature, which makes this comparison and validation impossible at present. It is understandable that such detailed data is difficult to collect in clinical or in vitro studies, and in the foreseeable future such experimental data will still be unavailable, thus researchers should rely on further refined CFD analysis in order to progress understanding of the area.

The present study yields the S-L relation during the aspiration intervention, and shows the interesting phenomenon that the suction force developed when the catheter tip is $0.1mm$ away from the thrombus surface is larger than that when the catheter tip is in full contact with the thrombus surface, under the flow system simulated. It is hard to say whether this numerically predicted response feature is truly consistent with the physical reality, given that due to software license restrictions, a mesh independent test has yet to be conducted. As the S-L relation during the aspiration intervention has significant impact on the design of new catheters and clinical operational protocols, this phenomenon deserves to be investigated in more detail in a future study.

The current CFD research studies a typical aspiration thrombectomy procedure, with the technical data including the geometries of the vessel and catheter, and the operational suction pressure etc., all set based on the information available from published clinical and in vitro test literature. The set of technical data used in this study cannot cover all the scenarios reported in the literature, so the response data reflects only a typical situation of the cerebral flow dynamics among the various patient conditions and the intervention procedures. Though such difference may cause some quantitative variation in the response data, it will not change the overall nature of the system response. In this sense, the current study can be used as a useful reference in the analysis of thrombectomy procedure.

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To be consistent with Lally et al's in vitro study ([14]) for validation, the current study considered the scenario that the catheter is placed concentrically with the vessel. In the situation that the catheter is not placed concentrically with the vessel but the axial direction of the catheter is parallel to that of the vessel, it is envisaged that the peak flow velocity, the streamlines, S-L relation etc will all deviate from the those in the concentrated case but the deviation will not be large, as long as the catheter is not purposely located near the inner wall of the vessel. However, if the catheter is not placed concentrically with the vessel and the axial direction of the catheter is not parallel to that of the vessel, then the flow condition will become much more complex, with flow condition and S-L relation etc. all becoming unpredictable and will have to be measured through specific experimental and/or CFD modelling studies. Besides this, it is understood that factors like the blood vessel size, the blood viscosity, the vessel elasticity, and the operating pressure etc also influence the blood flow dynamics in the studied case and these factors will all vary between individual patients. For example, a different diameter ratio of vessel/catheter will induce changes in the blood flow velocity and the slope of the S-L curve; elevated suction pressure may help to increase the suction force acted on the thrombus, but at the same time may also extract too much blood from the vessel as well as increase the tendency for the cerebral artery to collapse. These are all interesting topics and will be explored in the next stage of our modelling study.

5. Conclusion

The presented research used CFD analysis to model the blood flow dynamics in a simplified cerebral model. The general flow field features simulated agree well with the in vitro response as reported in the literature. The CFD study also provides detailed technical data including the peak velocity occurring at the catheter tip and the suction force-suction distance relationship during the aspiration thrombectomy procedure, which give useful new knowledge and have the potential to influence new catheter design and the clinical operational protocols during the thrombectomy intervention.

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