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Flow Analysis of Cerebrospinal Fluid inside Catheters used for Hydrocephalus Patients According to Brain MRI Image by Means of CFD

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ABSTRACT

(1) The treatment of hydrocephalus is the use of cerebrospinal shunts. These shunts are made up of different parts. One of the most important parts of these shunts is their catheter, which is placed inside the ventricle of the brain in order to drain cerebrospinal fluid. One of the most important problems of ventricular catheters is their clogging, which causes shunt replacement in 50-80% cases. Although many factors affect this congestion, one of the most important of them is the flow inside the ventricles of the brain with hydrocephalus; (2) Methods: The works of many researchers have mentioned the problem of flow inside the catheters, for this purpose two-dimensional simulation has been used. In this research, the two-dimensional image obtained through MRI has been used in the simulation in order to influence the real shape of the ventricles of the brain in the occlusion of the ventricular catheters; (3) Results: According to the investigations, the cause of clogging of most common catheters is the problem in the morphology and the way their holes are located; (4) Conclusions: A new design of catheters by changing the diameter and slope of the holes has been presented. It was found that conventional catheters are very susceptible to being closed by dead cells or cerebral ventricular tissue. Four types of catheters were examined, types 3 and 4 showed better performance with 50% and types 5 and 6 with 100% reduction in the probability of catheter hole closure.

1. Introduction

Although in the past, hydrocephalus was known as a disease of the brain, but its primary treatment, which consists of cerebrospinal fluid drainage, was defined and used in 1900. The initial definitions of valve and flow regime were presented by Payr [1]. In 1952, Nulson and Spitz, together with John Holter, the father of hydrocephalus in children, were able to report the first successful use of a shunt. Since then, the use of cerebrospinal shunts has been considered as a suitable treatment for hydrocephalus. But in the early years of its use, problems arose due to low production

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technology [2, 3]. From the beginning until today, the blockage of these shunts by dead cells and brain tissue is the most basic challenge of use, so that more than 40% of shunts become blocked in the first year of use, and they should be replaced [4-7].

Generally, about 50 to 80 clogging of brain shunts is due to clogging of their catheters [2, 4, 8, 9]. Although many parameters and factors affect this issue [10, 11], the most basic reason for this congestion is related to the flow of fluid and the way this fluid passes through the brain, causing hydrocephalus. Many researches have been conducted in 2003 in order to investigate the flow inside cerebral catheters [12, 13], in which two-dimensional simulations were used, and finally, it can be said that these simulations did not reach significant results. And none of their research has been able to establish a relationship between shunt blockage and flow characteristics. The only conclusion reached by this group is the fact that about 80% of the cerebrospinal fluid flows out of the two end holes of the catheter (Fig. 1). CFD is a powerful tool for analyzing flow patterns in complex geometries [14, 15]. Some researchers conducted extensive research on computational fluid dynamics of catheters [16, 17]. Galarza et al. conducted a flow study on five common types of catheters used in clinical practice, and finally concluded that the ventricular catheters on the market have an unbalanced and uncertain flow pattern, which the pattern is incremental from the beginning to the end of the catheter [16]. Also, this group presented a new catheter in which the diameter of the hole changes along the length of the catheter and makes the flow more uniform. Also, they came to the conclusion that if the flow enters the catheter uniformly, the possibility of clogging the holes decreases. In 2014, the aforementioned group presented a three-dimensional analysis of catheters with new shapes [18]. In this research, they changed the arrangement of the holes and the location and distance between the catheter holes, and finally they came to the conclusion that these new catheters, by changing the diameter of the holes and the number of holes, cause uniform entry. Fluid flow into the catheter as well as the uniformity of the flow along the catheter, finally as a general conclusion, they claimed that the uniformity of the flow reduces the chance of catheter blockage. In 2015, Galarza et el. conducted similar research to the previous one, and this time they changed the holes and the way they are arranged and also the diameter of the holes [19].

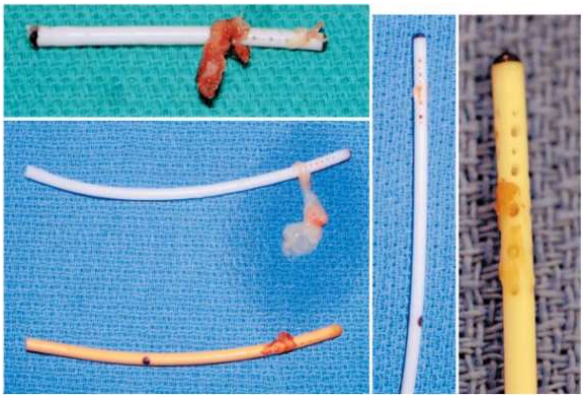


Fig. 1. Different types of catheters whose holes are stuck. As can be seen, there are more dead cells and brain ventricle tissue around the proximal holes [12]

So far, explanations have been given about simulating the phenomenon of flow inside cerebrospinal catheters, but the main problem that these researches have had is the lack of investigating a more realistic system. This means that all these researches have taken the brain system as a single cylinder and the flow as a fully developed flow, so that

the size of the catheter can be ignored compared to the surrounding environment. Although the authors themselves have admitted that the system under investigation is a very simplistic system. Fig. 2 shows the simulation system [16, 19]. As it is clear from Fig. 2, this system has an input and an output, the output of which is from the end of the catheter, which causes the current to pass through the holes of the catheter.

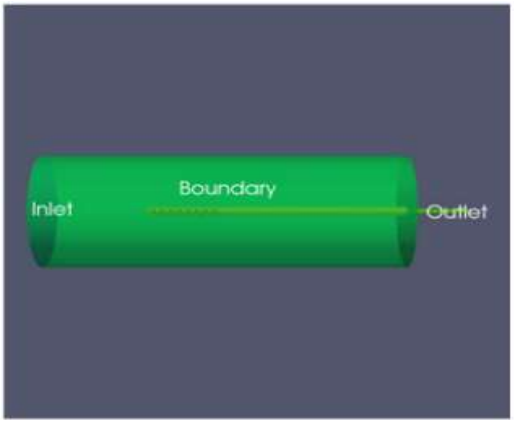


Fig. 2. Simplified assumptions of the catheter inside the cylinder [16]

The authors mentioned that this system will not meet the needs of simulating the system [16, 19] . As shown in Fig. 3, cerebral catheters are actually placed in the ventricular system of the brain. A lot of research has been done on investigating the flow of cerebrospinal fluid inside the ventricles of the brain. MRI image is also used in this research. According to the MRI image taken, the ventricles of the brain as well as the cerebral cortex are entered into the software that can read the image sequences. In these researches, they sometimes compare a healthy brain and a hydrocephalic brain according to the MRI image [20]. Also, new research has been done on the expansion of cerebrospinal fluid in a pulsed manner. In this research, in order to complete the solution and examine the system in detail, the pulsating nature of cerebrospinal fluid production is considered, which refers to the speed and pressure in different parts of the brain and spinal cord in systole or diastole [21-24].

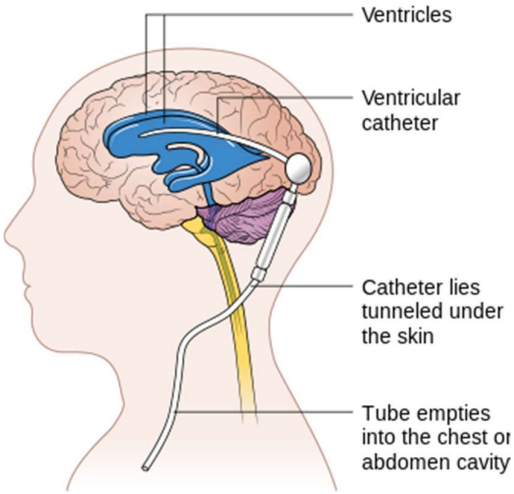


Fig. 3. shunt placed inside the ventricle of the brain

It should be mentioned that there has been works that have compared a healthy brain and a hydrocephalic brain, they have only presented the pressure and velocity curves and a special result regarding the use of shunts or the method of

treatment is not mentioned [21-23, 25]. Fig. 4 shows the two-dimensional simulation inside the brain system prepared according to the MRI image. The research done on simulating the flow of cerebrospinal fluid is much more than the research done on cerebrospinal shunts. But until now, no research has been done to integrate a precise MRI image and consider a catheter inside it.

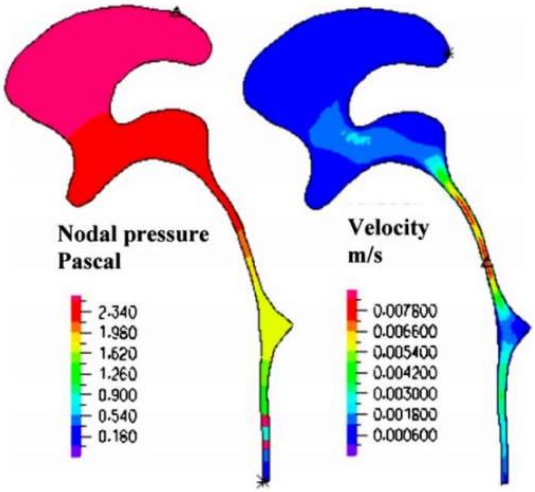


Fig. 4. Velocity and pressure profile inside brain ventricles [22]

1.1. Theory

In this part, the progress of the work seems necessary to simulate only the brain and cerebrospinal fluid. Table 1 first shows the process of modeling the geometry of the brain and its progress, as well as the boundary conditions used.

Table 1. Assumptions made in simplifying the simulation of the brain and its ventricles

Model	Simplification in brain simulation
Ursino [26]	Channel modeling, rigid boundary assumption, input constancy
Aroussi [27]	Assumption of rigid boundary, fixed input, not modeling the subarachnoid space of the brain
Gholampour [28]	Modeling the brain with unrealistic volume, fixed inputs, not modeling the brain SAS
Linninger [29]	2D modeling, modeling tissue as intracellular fluid

In table 1, there are brief about how researcher simulate the brain and cerebrospinal fluid. Although according to the assumptions, complete simulations have been done in the field of cerebrospinal fluid, but until now there is no real system in which the catheter is placed. The current research is investigating and simulating cerebrospinal shunts by means of MRI images inside the ventricles of the brain. This is done by placing a catheter inside a hydrocephalic brain. The details and the simulation method will be fully developed in the present study.

1.2. Statement of the problem and the necessity of simulation

CFD is an engineering tool to analyze flow in different systems. In this research, COMSOL software was used to simulate catheters in a specific system. For simulation, the Navier-Stokes equation has been used in the incompressible system (because it is liquid), which equations are coupled due to the geometry and become nonlinear as a result. The most important part of the simulation is taking the MRI image. In order to simulate, due to the limited possibilities, we have tried to use two-dimensional simulation. Two important parameters investigated in this project are the uniformity of the flow inside the catheter and the shear stress on the surfaces. According to the explanations

provided in the introduction, the more uniform the flow through the catheter, the less likely it is to become blocked. But the most important factor that affects the sticking or movement of dead cells or cerebral cortex cells is the shear stress factor on the critical surfaces of the catheter. Critical surfaces are surfaces where the possibility of cell adhesion increases. For example, the most clogging is related to holes far from the origin. The research of Thomale et al. [30] showed that 40-63% of the catheter-bearing cells are related to the outer tissue. Through histological research, it was found that most of these cells include gliosis, tissue cells, and immune cells. In the mentioned research, a catheter with fewer holes was designed and the authors claimed that this catheter has a lower possibility of clogging compared to normal cases, although they did not provide a parameter for their claim and only used experimental data. In addition, there has been no research that provides a logical relationship between a parameter other than the speed profile (which is not sufficient for the proper analysis of a flow parameter) and cerebral shunt occlusion. In this research, the surface tension parameter is considered in addition to the velocity profile parameter analysis in a more complete system (two-dimensional MRI image).

2. Method

In order to simulate, boundary conditions and governing laws are needed. As mentioned, the Navier-Stokes equation has been used in the non-compressible system (because it is liquid), where the equations are coupled due to the geometry and thus become nonlinear. Boundary conditions and values used are given in Tables 2 and 3 respectively.

Table 2. Boundary conditions and governing rules

Boundary conditions	Input	Output
Rigid Wall	Cerebrospinal fluid enters from the top of the third ventricle and lateral ventricle	(hydrocephalic brain) from the exit of the catheter (shunt)
No slip condition on the walls	Fixed production of 600 cc per day	Fluid exit from the catheter

According to Table 2, these conditions are considered as boundary conditions for input and output. It is different in some references that the production of this liquid is 600 cc [23, 28]. Although this value is trivial on simulation. Because the purpose of this simulation is to check the shear stress and catheter speed profile. Therefore, if a value is chosen for this purpose, the comparison of different parts will not be disrupted because the only purpose is comparison. In order to simulate, we need two constants of density and viscosity of cerebrospinal fluid. Cerebrospinal fluid is always assumed to be Newtonian in all articles. The reason for this assumption is that this liquid is very similar to water. For this reason and according to the articles, the parameters of Table 3 are considered as the input of the COMSOL program [23, 28].

Table 3. Value of density and viscosity

Parameter	Value
Density	1000 Kg/m3
Viscosity	0.001 Pa.s

Considering that the software used in this simulation is COMSOL, the process of investigation is finite element. Due to the fact that the design of the catheters will be explained in the following, and in addition, their structural shape is also different, but in all these models, the internal diameter of the catheter is 1.5mm and its external diameter is 3mm.

The simulation process is such that we place the shunt inside one of the right or left ventricles. Because the shape is two-dimensional, in fact, the right and left ventricles are placed on top of each other. This placement of the shunt should be such that it exits behind the head. As shown in Fig. 5a, the white part that is placed between the brain and the shunt is actually the part that the COMSOL software considers as the wall, and therefore, the cerebrospinal fluid after production at a constant speed (the assumption given in Table 2) moves towards an exit. Due to the fact that the brain has hydrocephalus, the fluid cannot escape, but when we put the shunt inside the head, it moves towards the outlet after passing through the holes of the shunt. It is clear that after the passage of fluid on the holes of the shunt as well as its internal section, a shearing force is applied, and the references mentioned that the lower this shearing force is, the more likely the catheter will be closed by dead cells. The meshes used for numerical solution by COMSOL software can be seen in Fig. 5b. Also, as can be seen in Figure 5c, the independence analysis of the number of meshes is suitable for about 8 million meshes.

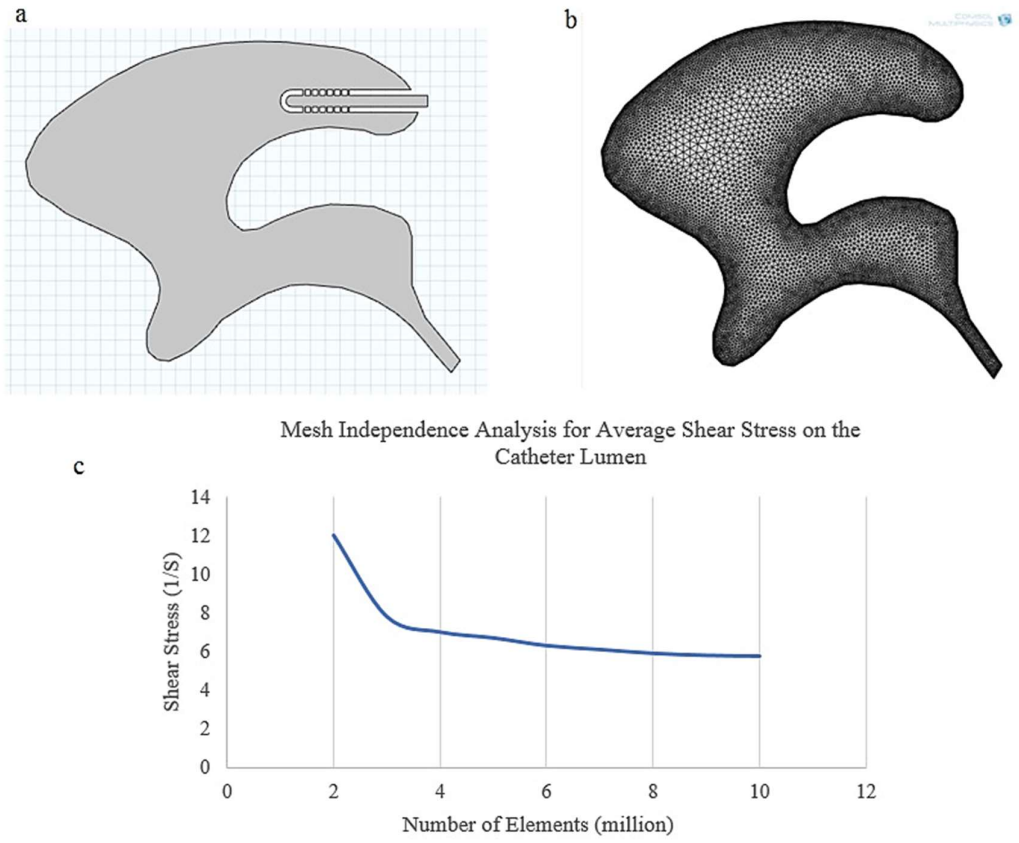


Fig. 5. (a) MRI image of the brain with the catheter inside; (b) The shape of the meshes produced by COMSOL software; (c) mesh independence analysis for average shear stress on the catheter lumen

3. Result and discussion

According to the introduction section, shear stress is considered the most important parameter in the closure of catheter holes, and for this reason, six types of catheters are examined in this section. The first and second types are old designs that are now used for patients. But the last four designs are optimized designs which are explained in their own section.

3.1. Design of the first type of catheter

At first, it is assumed that there is a catheter with the same hole diameter and a completely simple design. In this section. This is the simplest mode considered. The size of the internal lumen and the external diameter are the same numbers as mentioned before. In this part, the inner diameter of the holes is considered equal to 0.2mm, but in the next parts, this diameter will change, which will be discussed and the results will be presented.

As can be seen from Fig. 6, the velocity profile within the cerebral ventricles is shown. It should be noted that the units written for geometry are in millimeters. The speed units are in meters per second, which are consistent with the speeds mentioned in the articles. Fig. 7 is actually the same as Fig. 6, but enlarged the catheter part. These figures only give information about the speed profile. According to the aforementioned explanations and articles, the more uniform the profile shown in the catheter is, the less likely the catheter will be blocked. Here, as can be seen, most of the current enters from the proximal holes. In Fig. 8, which actually shows the shear stress along the length of the catheter, it is clear that the stress on the inner surface of the holes has a large value, which is not desirable. Holes are reduced by dead cells. Because the presented image has only a qualitative judgment, in the next part the average numbers for different parts of the catheter are calculated.

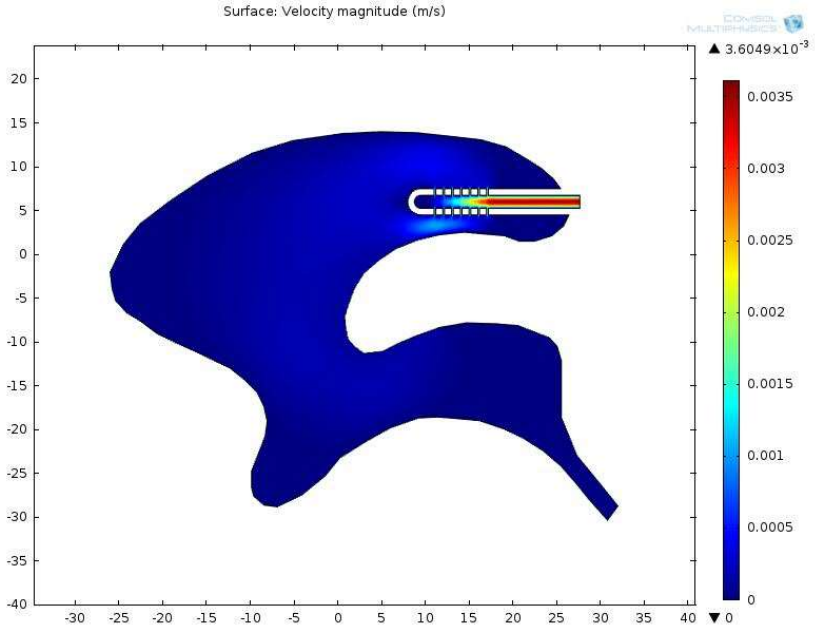


Fig. 6. Velocity profile inside the catheter and brain ventricles for the first type catheter

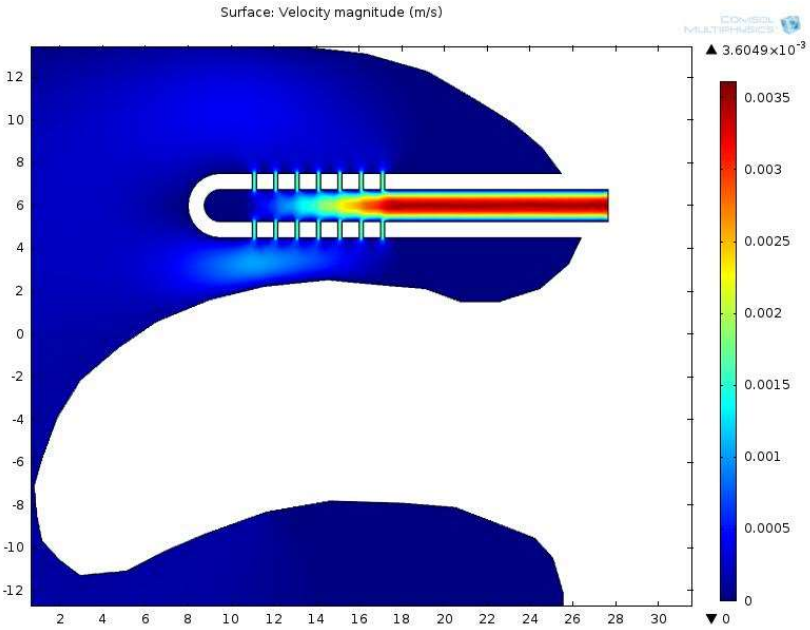


Fig. 7. Magnified velocity profile in the right (or left) ventricular part of the first type of brain catheter

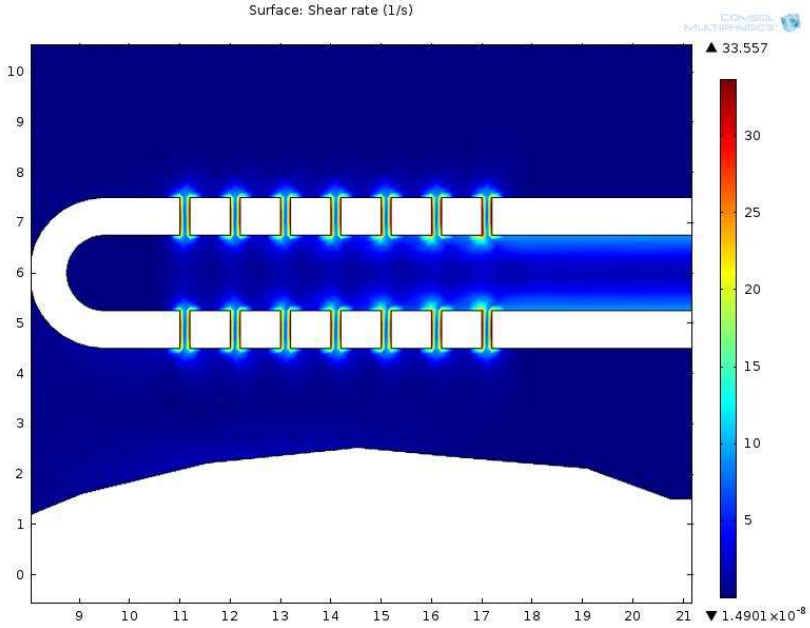


Fig. 8. Shear stress profile for first type catheter

As can be seen from Fig. 9, the value of shear stress is drawn for the inside of the lumen of the holes. In this case, because the holes are in a specific x, that means their beginning and end are on the same point, so we have to use Arc length. It can be seen that the shear stress is higher in the proximal parts. This is actually a proof of the correctness of the simulation. Because according to experimental data, the blockage of proximal holes is more than other holes. Fig. 9 shows this fact. The point is that the shear stress itself on the inner wall of the holes is not linear and has an oscillation.

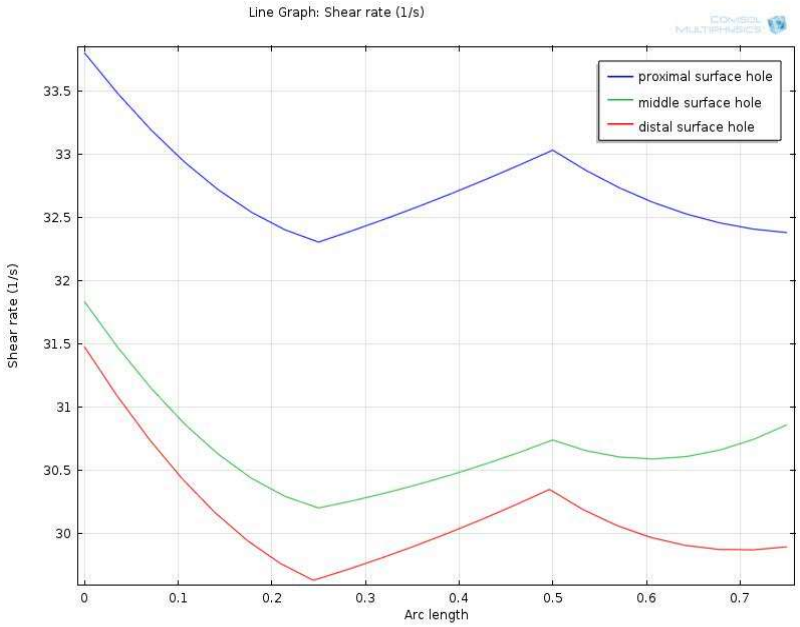


Fig. 9. Shear stress inside the hole lumen for three holes (proximal, middle, distal)

From the beginning of entering (i.e. from the outside to the inside), the value of the shear stress is at its highest value, and the more it enters the inside, the shear stress decreases. Until we reach a minimum. Due to this fact, the possibility of the catheter getting stuck in the outer part of the catheter is more likely. This has also been proven by experimental data. However, we reach an extremum in shear stress at about 50% of the length of the double hole. Although this amount of tension is lower at the beginning of the entrance to the hole, but considering that the other two sides have lower values than the extreme point, it is a good point for cell growth and this thesis can be proposed. This extreme point is the gathering place of cells that are looking for a place to multiply and grow. Fig. 10 actually shows the shear stress inside the catheter lumen.

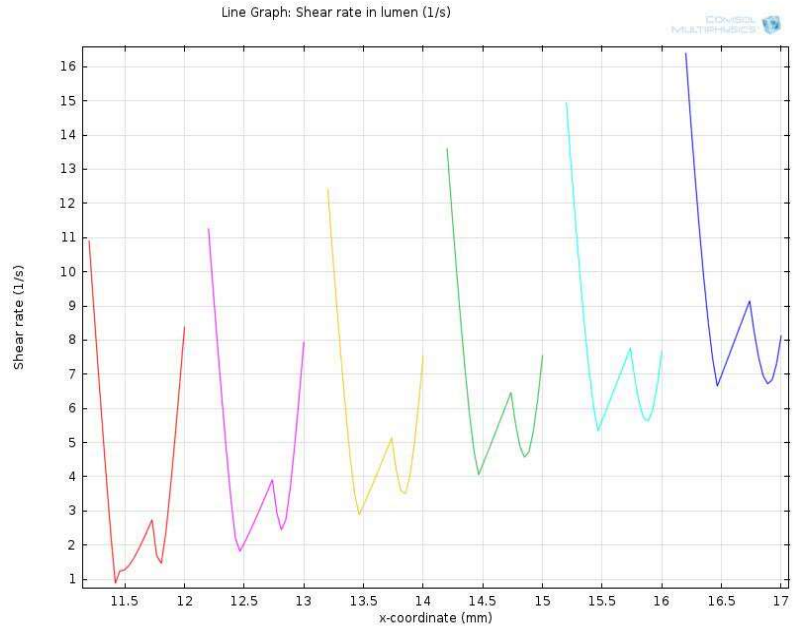
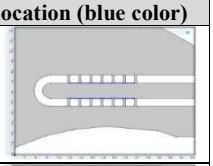
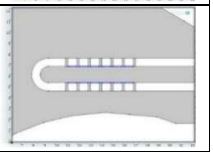
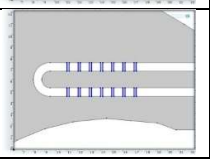


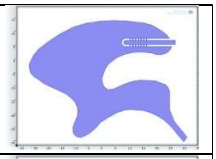
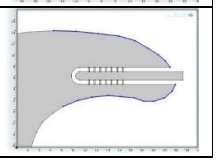
Fig. 10. Shear stress inside the catheter lumen based on the length of the catheter

In this part, because the position of x changes during the movement of the catheter, we do not need to use Arc length. The parts where the diagram is cut are related to the areas where we have holes. First, the length is 11/5 corresponding to the distal points. It can be seen that with the increase of x, the amount of shear stress on the lumen of the catheter increases. But the significant point is the numerical scale of Fig. 9 and 10. The numbers in Fig. 10 are about ten to fifteen units less than the numbers in Fig. 9, which shows that the possibility of blockage in the lumen of the catheter holes is more than the lumen of the catheter itself, which is another experimental data report. There is a point like Fig. 9 and 10 also has a peak. This peak is placed almost in the distance between the two holes. These points have more shear stress than other places, but in general, these numbers are small compared to the shear stress applied to the internal lumen of the holes. But these central points between the two holes are suitable places for dead cells to get stuck due to the higher shear stress.

In Table 4, we have given the numerical values for ease of comparison. As can be seen, the amount of shear stress on the lumen of the catheter is about 6 (per second). While the average shear stress applied to the lumen of the holes, the value of 31 (1/S) is reported. This also gives the same result as we got in the previous part. In other words, according to the explanations given, because the shear stress on the lumen of the holes is more, we come to the conclusion that the possibility of dead cells getting stuck in these parts is more. This point is proven according to experimental data. It can be seen that the average shear stress on the lumen of the catheter is lower than the average shear stress on the lumen of the holes. But the average shear stress on the entire surface of the brain ventricle is much lower compared to the aforementioned numbers, in addition, the average shear stress on the surface close to the brain catheter is higher than the average stress on the entire surface of the brain ventricle. This can also be a proof that this simulation, which took place inside the brain, has an answer that is twice as accurate as other articles. The reason is that the average stress in the end part of the right ventricle (or left ventricle) is almost twice the amount of stress applied to the whole brain. If we consider the whole brain as a cylinder (which other articles did), then the tension in the area near the catheter is equal to the tension applied to the entire cylinder, which will not give the correct answer (Although other articles also did not provide analysis for shear stress).

Table 4. Image of the location of averaging

Parameter	Amount (1/S)	Image of averaging location (blue color)
The average shear stress on the catheter lumen	5.905	
The maximum shear stress applied to the catheter lumen	16.495	
The average shear stress on the lumen of the holes	31.280	

The average shear stress on the entire surface of the ventricles of the brain	0.169	
The average shear stress on the surface close to the brain catheter	0.296	

3.2. Catheter with different hole diameters (second type catheter)

In this case, a catheter has been designed in which the diameter of the holes is not uniform and fixed as in the previous case, but the diameter of the holes changes from 0.17 to 0.3 mm with steps of 0.2 mm. As shown in Fig. 11, the speed profile is more uniform than the previous state, and this is due to the fact that as we move from the distal part to the proximal side, the diameter of the holes decreases. From Fig. 12, it is clear that the shear stress has decreased by about 7 units (1/S), which means that with this change, we have been able to reduce the shear stress.

But the most important result and decision that can be made is shown in Fig. 13. In the previous part, it was found that the shear stress on the proximal holes was higher than on the distal one. But here the issue is completely different. This means that the proximal holes have less stress. It means that now it is possible to close the distal holes more than the closing of the proximal holes. With these two examples, we realize that we can find a more optimal state, besides that the peaks in Fig. 13 have a lower height than Fig. 9. And as it was said, the shear stress values are lower than before, which promises less closing of the holes by dead cells. Fig. 14 is the same as Fig. 9. But here the amount of shear stress is slightly increased, which is also shown in Table 5. This increase has no effect on closing because the numbers have small values that can be ignored compared to the lumen of the holes.

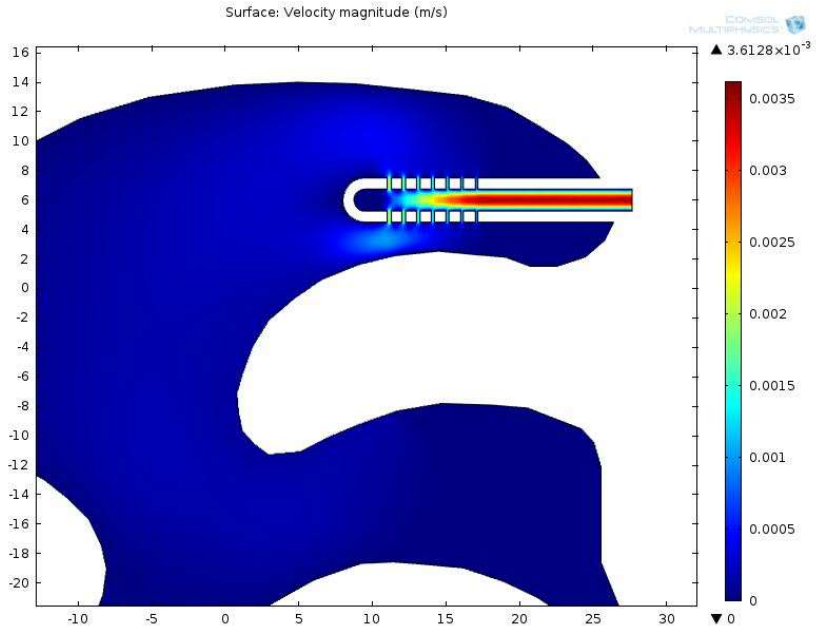


Fig. 11. Velocity profile inside the catheter and brain ventricles for the second type catheter

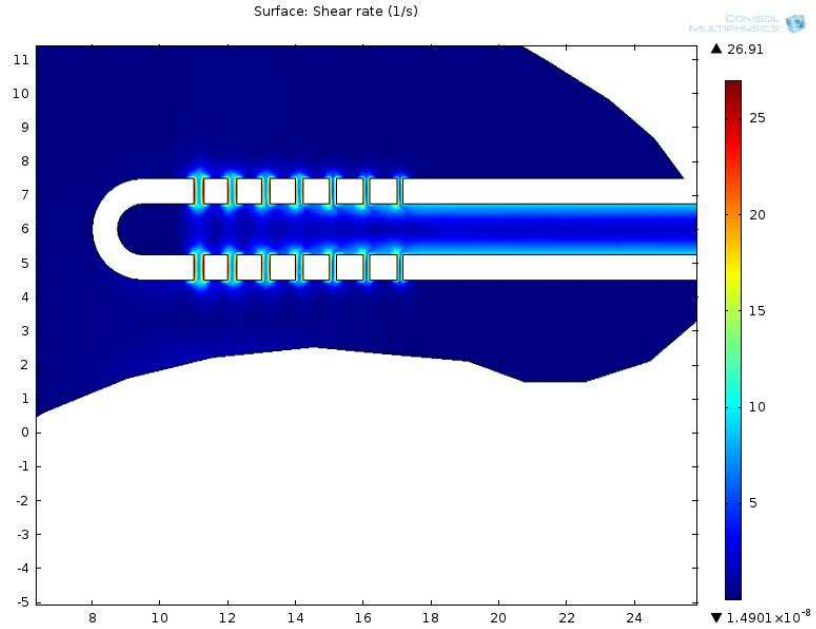


Fig. 12. Magnified velocity profile in the right (or left) ventricle of the brain with type II catheter

Table 5 is actually the same as table 4, but in this case, it is rewritten with holes of different diameter. It should be noted that in this part and the following parts, due to the stability of the column related to the figures, repeating them again has been omitted. As a comparison with the previous state, only the average shear stress on the catheter lumen has increased, but the rest of the shear stress values have decreased. This phenomenon is in our favor. This means that the amount of shear stress on the lumen of the catheter is small, and with a small increase, there is no change in the closing or non-closing of the lumen by dead cells. It can be seen that the shear stress on the lumen of the holes has been significantly reduced, so that we had a reduction of about 10 units (1/S), which means a reduction in the probability of the catheter holes being closed by dead cells.

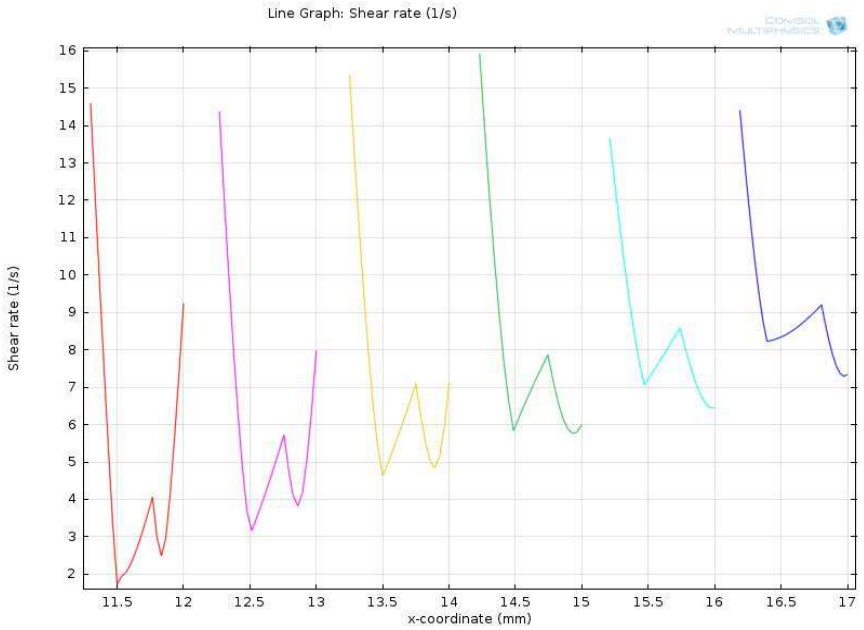


Fig. 13. Shear stress inside the catheter lumen based on the length of the catheter

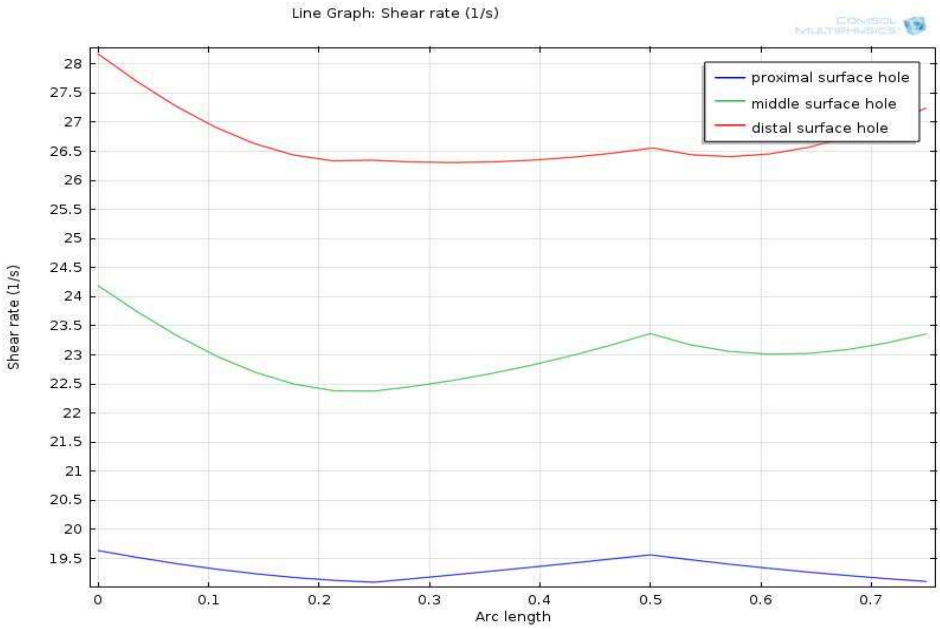


Fig. 14. Shear stress inside the lumen of the holes for three holes

Table 5. Shear stress values for the second type of catheter

Parameter	(1/S)
The average shear stress on the catheter lumen	7.113
The maximum shear stress applied to the catheter lumen	16.242
The average shear stress on the lumen of the holes	22.884
The average shear stress on the entire surface of the ventricles of the brain	0.165
The average shear stress on the surface close to the brain catheter	0.244

3.3. Catheter with a new design (third type catheter)

According to the previous part, we noticed that if the diameter of the holes decreases from the distal to the proximal part, the shear stress inside the catheter holes decreases. In this design, there is the same process (that is, the diameter of the holes is reduced) and in addition, there are holes with an angle of 25 degrees inside the catheter.

As shown in Fig. 15, changes have been made in the arrangement of the holes. The purpose of these changes is to investigate the shear stress on the lumen of the catheter and the lumen of the holes compared to the changes in the holes. Fig. 15 shows the speed profile, which can be seen there are not many changes from the previous state, although the profile has become somewhat more uniform. According to the aforementioned explanations, this uniformity prevents dead cells from sticking to the inner surface or the lumen of the catheter. In this case, as in the second case, the shear stress applied to the proximal part is lower than the value applied to the distal part. But this method increases the shear stress on the distal part. This means that this method is not suitable for the lumen of holes. As we will see in Table 6, the amount of shear stress in the lumen of the catheter is higher than the previous two cases. Fig. 17 shows the shear stress distribution in the catheter lumen wall. As in the previous cases, we have a maximum tension almost in the center between the two holes (inside the lumen of the catheter), which actually indicates the right place for dead cells to get stuck. For more complete investigations, we need numerical analysis. For this reason, we arrange Table 6 to provide us with statistical data.

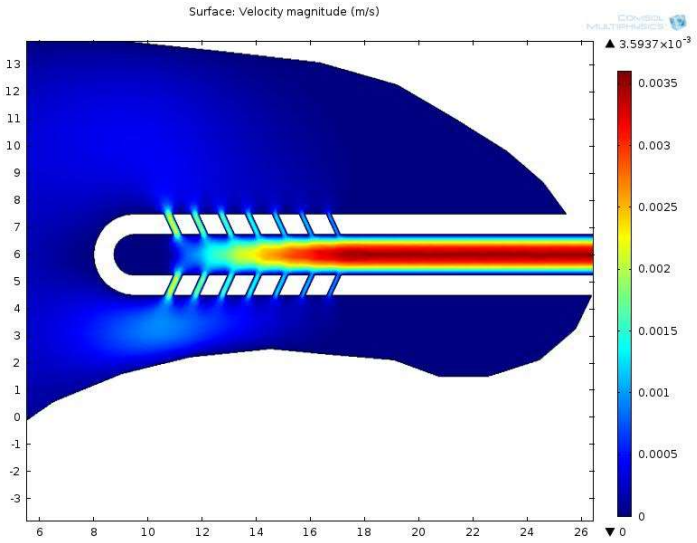


Fig. 15. New catheter design (third type catheter)

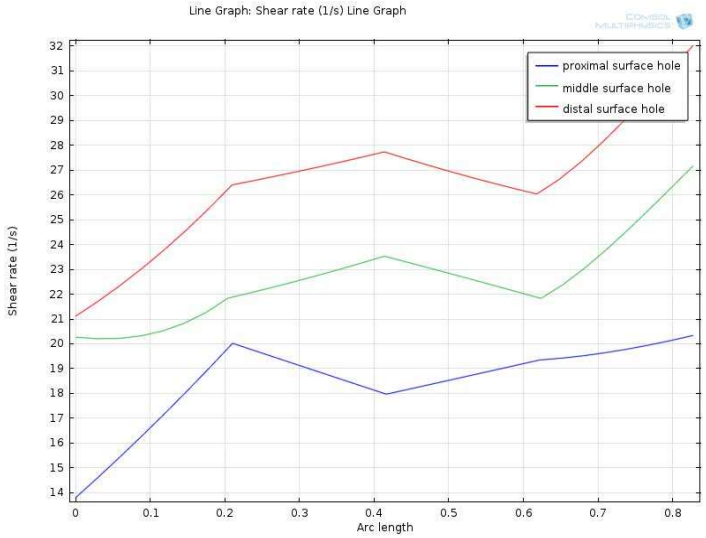


Fig. 16. Shear stress inside the hole lumen for three holes (proximal, middle, distal)

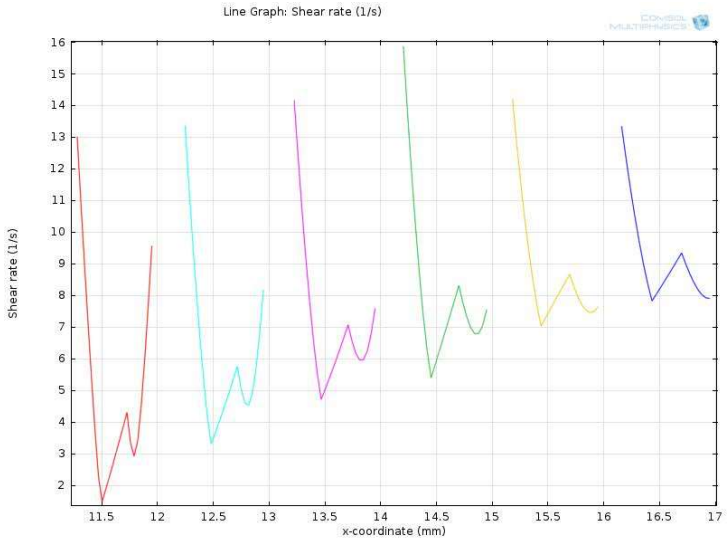


Fig. 17. Shear stress inside the catheter lumen based on the length of the catheter

As can be seen in Table 6 and according to the two aforementioned tables (4 and 5), the average amount of shear stress on the catheter lumen has increased slightly. Also, the average shear stress on the lumen of the holes is slightly reduced, and this reduction is the same as the second case, and it can be a suitable catheter for design and construction (compared to the first catheter), but due to the small change compared to the second catheter, the second catheter can be considered more appropriate.

Table 6. Shear stress values for the second type of catheter

Parameter	(1/S)
The average shear stress on the catheter lumen	7.355
The maximum shear stress applied to the catheter lumen	15.872
The average shear stress on the lumen of the holes	22.489
The average shear stress on the entire surface of the ventricles of the brain	0.165
The average shear stress on the surface close to the brain catheter	0.213

3.4. Catheter with a new design (4^{th} type catheter)

As it was clear from the second catheter, the reduction of the diameter from the distal to the proximal part reduces the surface tension and thus reduces the probability of the catheter holes being stuck by dead cells. In this new design (Fig. 18), the same observed principle has changed due to the inclination of the holes. These changes have been applied in such a way that some of the holes are placed at an angle of 25 degrees and some others at an angle of -25. Figs. 19 and 20 and Table 7 will show additional information. As it is clear from Fig. 20, as in the previous two cases, with these changes applied, the proximal surface of the holes has less shear stress. In addition, the high peak that was seen in number one has now almost flattened out. Fig. 19 has peaks and minimums a little more than the previous three cases. The reason is the special shape of the catheter. In this case, as can be seen, a part of the lumen of the catheter has a larger surface and another part has a smaller surface. The part that has a lower surface seems appropriate. The reason is that in this case the shear stress reaches a small amount, which means that these small places are not suitable for cells to stay.

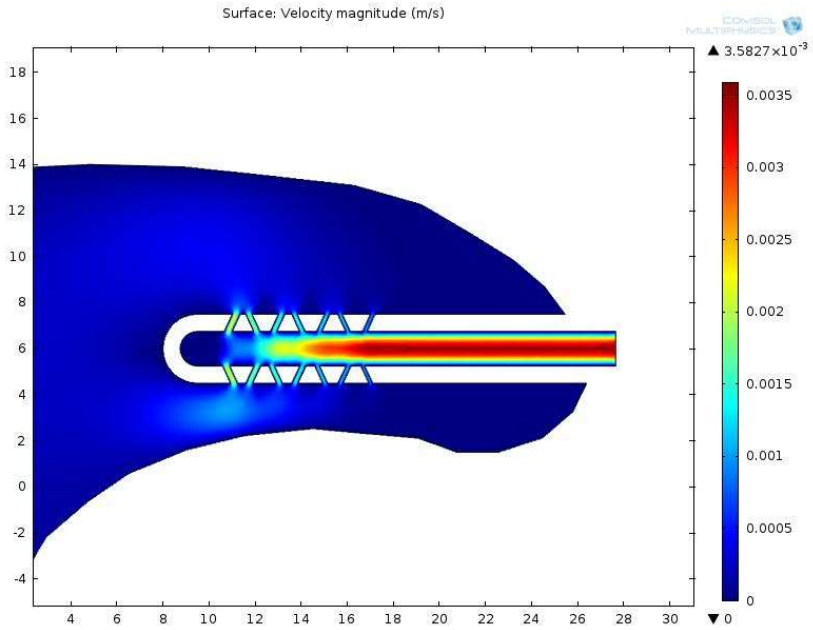


Fig. 18. New catheter design (fourth type catheter)

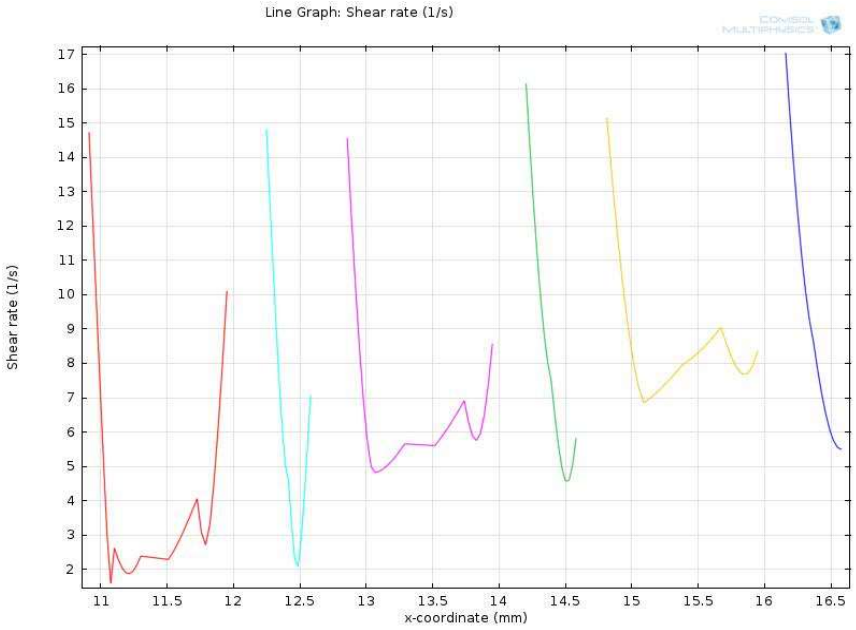


Fig. 19. Shear stress inside the catheter lumen based on the length of the catheter

As can be seen from Table 7, the average value of the shear stress on the lumen of the catheter is higher than the first case and less than the second and third cases. In fact, this design is placed between the two mentioned designs. But because this number is small and dead cells are mostly stuck in the lumen of the holes, it is not very important. The most important number for design is the average shear stress on the lumen of the holes. By comparing this number with other ones, we realize that this catheter has a better performance than the first type catheter and is almost in the same row as the second and third catheters. Also, according to the speed profile, we notice that the speed profile has a good uniformity. The uniformity of this profile is better than the speed profile of type one catheter, also the speed profile is suitable as the second and third mode.

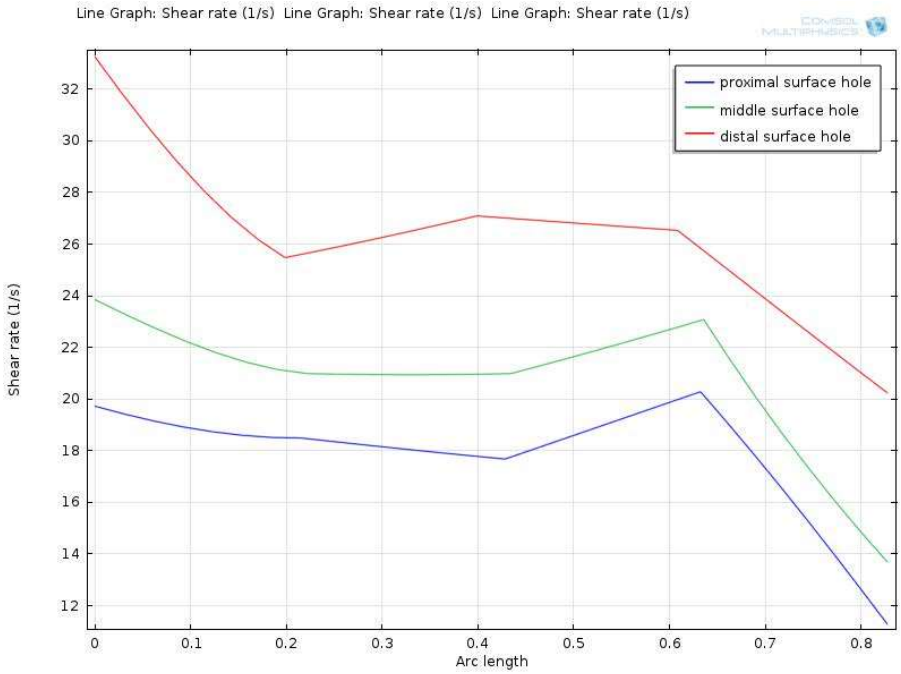


Fig. 20. Shear stress inside the lumen of the holes for three holes (proximal, middle, distal)

Table 7. Shear stress values for the second type of catheter

Parameter	**(1/S)**
The average shear stress on the catheter lumen	6.709
The maximum shear stress applied to the catheter lumen	17.048
The average shear stress on the lumen of the holes	22.335
The average shear stress on the entire surface of the ventricles of the brain	0.168
The average shear stress on the surface close to the brain catheter	0.232

3.5. New design of catheter (5th type catheter)

According to the explanations, we consider a new design of the catheter. This catheter is designed according to the design of previous catheters and their results. As can be seen, its design is such that it adds a slope inside the holes so that the diameter of these holes decreases from the distal to the proximal part (Fig**.** 21).

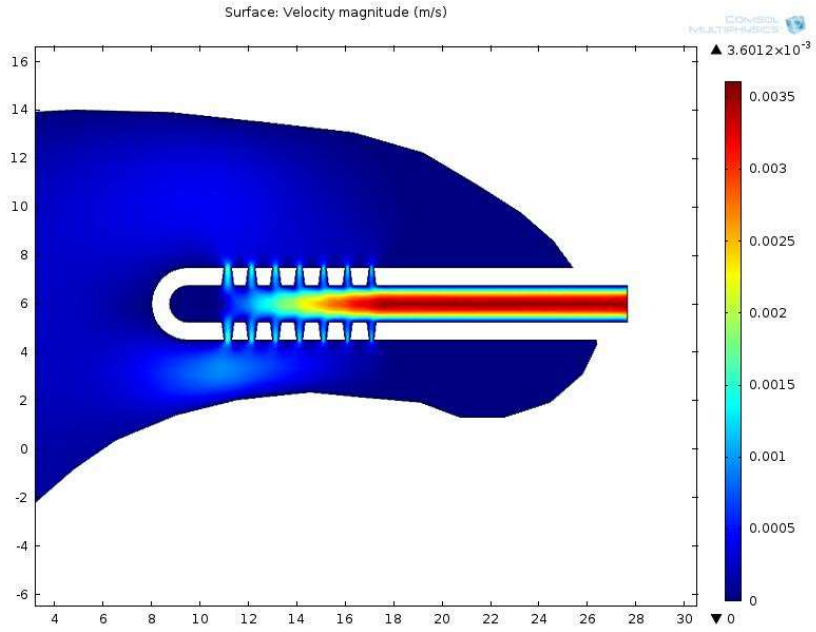


Fig. 21. New catheter design (5th type catheter)

Important points are specified in this structure. As it is clear from Fig. 22, the amount of shear stress in the lumen of the holes is almost equal and this is an important thing that improves the performance. In addition, the maximum shear stress is about ten units (1/S) less than other cases. This means that the possibility of the hole being blocked by dead cells is reduced by forty percent. This is an important result that is also taken in the next figure. As can be seen in Fig. 21, the velocity profile has also become more uniform and it is agreed with the claims of other articles that the uniformity of the velocity profile has an effect in preventing the holes from clogging.

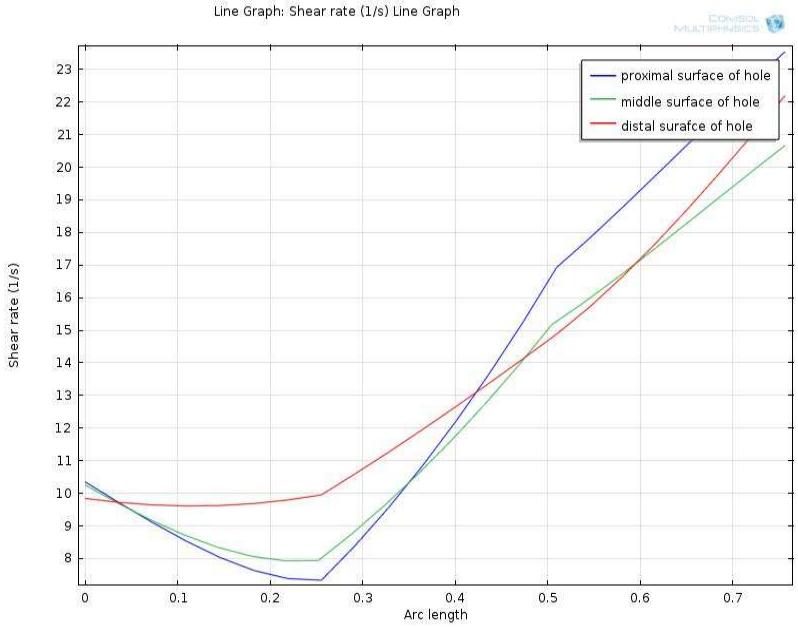


Fig. 22. Shear stress inside the hole lumen for three holes (proximal, middle, distal)

In addition, in Fig. 22, almost an upward trend can be seen, which does not have extremes like the previous trends. When the stress graph becomes extreme, the possibility of the dead cell getting stuck in the hole increases because there is an area where the cell can settle and multiply to some extent, and these places lead to the dead cell to get

stuck. But this catheter structure does not have such extremes. Fig. 23, as in the past, shows the shear stress inside the lumen of the catheter itself. A point that should be paid special attention to is that, like the diagram in Fig. 22, there is no extremum here either. In simpler terms, when passing through the walls of the catheter from the distal to the proximal part, the total tension is being added, but this addition between the two holes is continuously decreasing, which is a very important point, and this prevents the hole from closure of the main lumen of the catheter. For a more detailed numerical analysis of this system and to understand the main points, it is necessary to form a table of numerical averages, as in the previous parts, for this purpose, Table 8 has been prepared.

As can be seen in Table 8, almost all values of shear stress have decreased. In other words, this system is less likely to be closed by dead cells compared to all previous modes. The average value of the shear stress on the lumen of the catheter is almost one unit (1/S) less than the previous cases, which according to the previous explanations, this value is not an important parameter. The maximum shear stress applied to the lumen of the catheter is also about three units less than the previous cases, which indicates the proper design of the catheter. But the most important part of the design is the average shear stress on the lumen of the holes, which has been reduced by almost ten units compared to the previous best case.

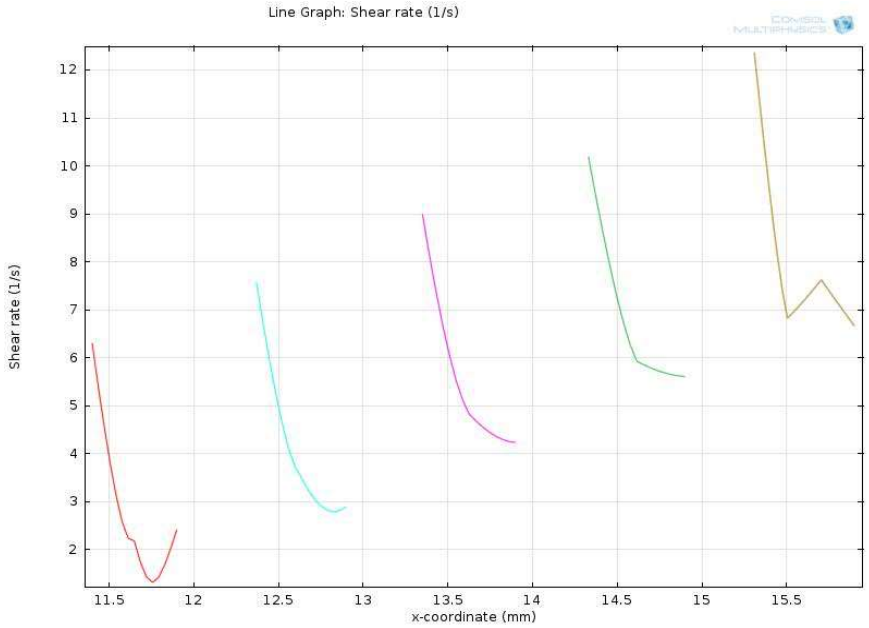


Fig. 23. Shear stress inside the catheter lumen based on the length of the catheter

This point is very important and the same numbers and points mentioned above are a proof of the proper performance of this catheter. But the average shear stress on the entire surface of the brain is also reduced compared to other cases, in other words, this catheter causes less stress to be applied to the tissue of the ventricles of the brain. Also, the last row of the table, which is the average stress on the surface close to the brain catheter, has decreased significantly. In other words, this catheter with this special design causes less tension to enter the surface of the ventricle of the brain, which can have a significant effect on the nausea of the shunted person.

Table 8. Shear stress values for the second type of catheter

Parameter	(1/S)
The average shear stress on the catheter lumen	6.104

The maximum shear stress applied to the catheter lumen	13.193
The average shear stress on the lumen of the holes	13.204
The average shear stress on the entire surface of the ventricles of the brain	0.152
The average shear stress on the surface close to the brain catheter	0.224

3.6. New design of catheter (sixth type catheter)

Considering that the above-mentioned design was suitable and had significant features, therefore, as the last design, we assume that the holes are incomplete cones like the previous case, which this time, unlike the previous case, created holes inside the catheter (Fig**.** 24). As in the previous cases, the diameter of the incomplete cones decreases from the distal to the proximal side.

According to Fig. 25, it can be concluded that, like the previous state where the shear stress was increasing, the shear stress has become a decreasing state in all places, which is a valuable thing. The reason for the importance of these two states (ascending or descending) is that in this state there is no extremum in which the shear stress wants to take the maximum value. This is because at these maxima, the possibility of blocking or getting stuck in the cell increases a lot. This is one of the reasons why these two catheter structures are good. According to Fig. 24, the most uniform speed profile is related to this mode. In other words, this state and the previous state (incomplete cone holes) are the best states that can be considered for the design of a catheter. Fig. 26, like the previous parts, has drawn the diagram of shear stress inside the lumen of the catheter.

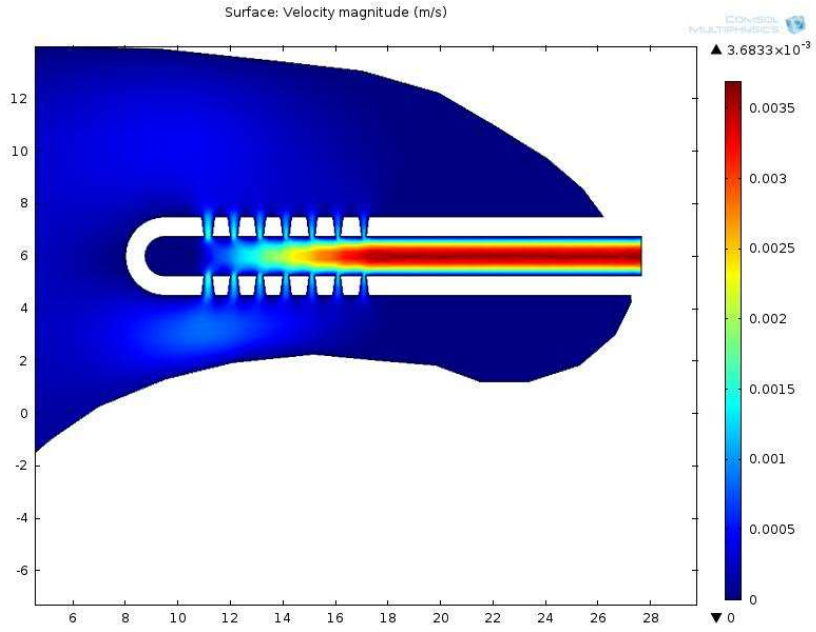


Fig. 24. New catheter design (sixth type catheter)

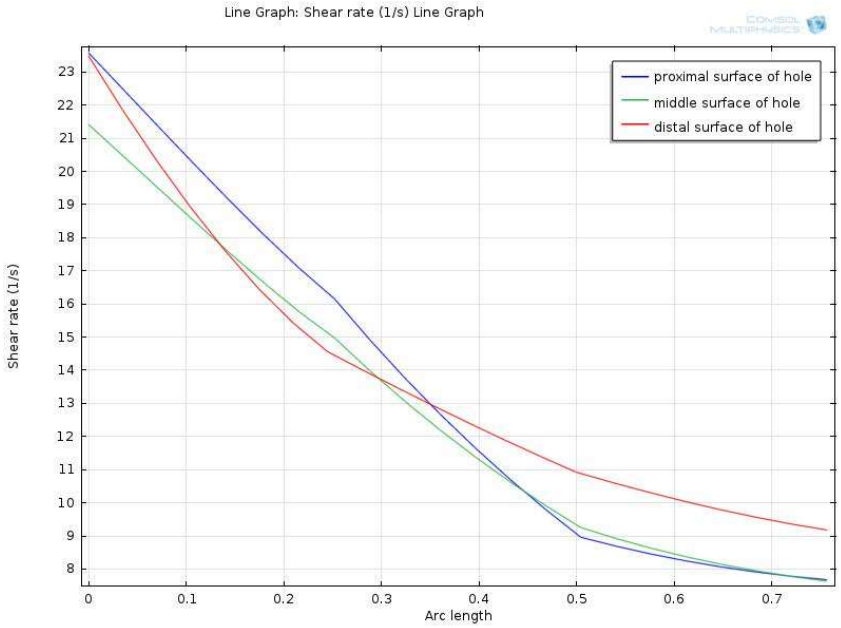


Fig. 25. Shear stress inside the lumen of the holes for three holes (proximal, middle, distal)

Like the previous cases, an increasing trend is observed from the distal to the proximal part, and this increase is slightly lower than the previous cases. It is an important point that the shear stress takes a small amount. Fig. 22 is actually the best state that the shear stress profile can take. A peak is also observed in the tension part inside the lumen of the catheter. Like the previous parts, this peak is located almost in the middle between two holes. This issue is not very desirable, but it should be noted that this amount of shear stress is on a small scale and does not have such an effect on the sticking or not sticking of the catheter holes. So, it can be concluded that the qualitative evidence, i.e. the shapes, have a claim on the appropriateness of this catheter design. Table 9 shows the corresponding numerical values.

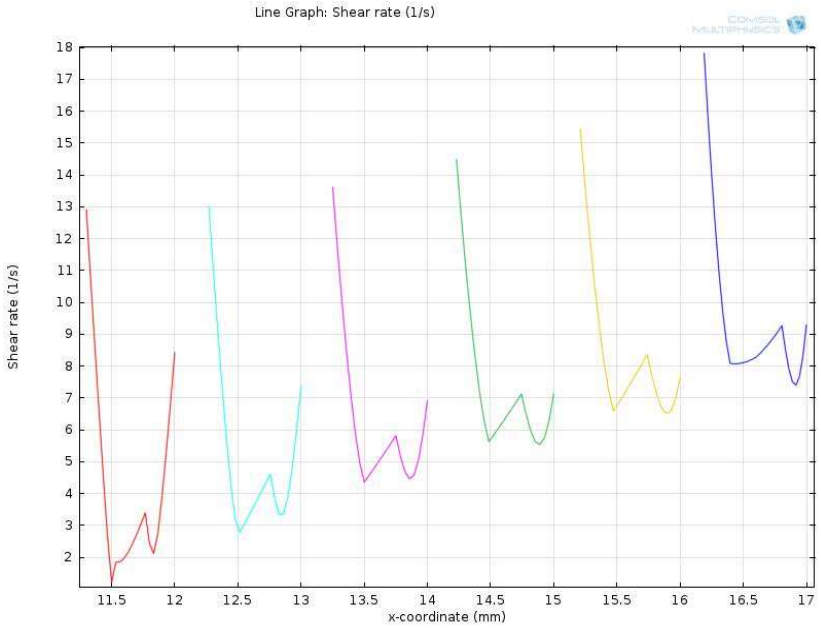


Fig. 26. Shear stress inside the catheter lumen based on the length of the catheter

Table 9. Shear stress values for the second type of catheter

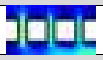
Parameter	(1/S)
The average shear stress on the catheter lumen	6.808
The maximum shear stress applied to the catheter lumen	17.834
The average shear stress on the lumen of the holes	13.357
The average shear stress on the entire surface of the ventricles of the brain	0.148
The average shear stress on the surface close to the brain catheter	0.195

The average shear stress on the catheter lumen is the lowest in this case. The maximum shear stress applied to the lumen of the catheter is greater than before, which can be the weak point of this model. But the most important parameter of the catheter design, i.e. the average shear stress on the lumen of the holes, is almost equal to the previous state with a slight change. This means that this catheter with this design has the minimum possibility of getting stuck or closing the holes by the dead cells in the ventricle of the brain. Another unique feature of this design is the minimal average shear stress on the entire surface of the brain, as well as the minimum average shear stress on the surface close to the brain catheter. This means that this type of catheter with this special design causes minimal nausea in a person with hydrocephalus disease, which can be one of the parameters that the doctor can consider in choosing the type of catheter.

As a conclusion of the simulated six catheters, the parameters and figures of the six cases are shown in Table 10. This table actually shows the characteristics of designed catheters. The first line is related to the shear stress on the catheter lumen. As mentioned, this value is not so important because it is a small number, but for the sake of comparison, the first catheter with a simple structure has minimum tension. No significant difference was observed in the shear stress on the catheter lumen between the discussed structures.

The second row of Table 10 shows the maximum shear stress on the catheter lumen, which is an important parameter. So that this maximum indicates the most likely blockage of the catheter lumen. But the most important number in this table is the average shear stress on the lumen of the holes. According to the explanations, the lower the shear stress, the less the possibility of closing the hole. As can be seen, in the first catheter, which is common and customary in hydrocephalus patients, the possibility of dead cells clogging is almost 50% more than the second and third type and about 100% more than the fifth and sixth type catheter.

Table 10. Shear stress values for six types of catheters

	(1/S)					
						
Parameter	**1**	**2**	**3**	**4**	**5**	**6**
The average shear stress on the catheter lumen	5.905	7.113	7.355	6.709	6.104	6.808
The maximum shear stress applied to the catheter lumen	16.495	16.242	15.872	17.048	13.193	17.834
The average shear stress on the lumen of the holes	31.280	22.884	22.489	23.335	13.204	13.357
The average shear stress on the entire surface of the ventricles of the brain	0.169	0.165	0.165	0.168	0.152	0.184
The average shear stress on the surface close to the brain catheter	0.296	0.244	0.213	0.232	0.224	0.195

This shows the inefficiency of the catheters in the market. These results were obtained only with computational fluid dynamics and the use of brain MRI images in two-dimensional coordinates. The best type of catheter is the fifth and sixth. But if the technology to make them is not available or expensive, making the third and fourth items also reduce

the probability of blocking by 50%, which is very efficient. As can be seen, the fifth and sixth catheters, promises to reduce the nausea caused by the inefficiency of the catheters in hydrocephalic patients.

4. Conclusion

In this research, it was found that conventional catheters are very susceptible to being closed by dead cells or cerebral ventricular tissue. Four types of catheters were examined, types 3 and 4 showed better performance with 50% and types 5 and 6 with 100% reduction in the probability of catheter hole closure. For this analysis, computational fluid dynamics with the MRI image of the brain ventricle and the analysis of the flow inside the holes and lumen of the catheter have been used. Shear stress is considered to be the most important factor in catheter hole clogging (although in this project, the uniformity of the velocity profile is also analyzed) so that the probability of catheter clogging increases with the increase of shear stress.

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