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Numerical Study of the effect of three leaflet opening angles on the blood flow through a bileaflet mechanical heart valve

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Abstract: The success of the operation and the heart performance, after the valve replacement surgery count on the influence of the performance of the valve. Recently, most studies have been done on Bileaflet Mechanical Heart valves (BiMHVs). Three different angles were selected, different results were obtained, flow conditions were stabilized, and limit conditions were imposed at constant entry speed (1 m/s) and exit pressure (0 Pascal) The angles were (43°, 63°, 83°), respectively, and for flow characteristics a steady, homogenous and incompressible. The target of this study was to examine the velocity distributions for the blood flow by using the bileaflet mechanical heart valve, with; the three angles were mounted in the Aortic location on diagonal angles. The calculation method used here was Finite Element Analysis (Ansys V14). Reynolds number was used to evaluate the flow. The results obtained from this study confirmed that the lowest speed was recorded at the largest opening angle completely and vice versa and therefore, the best position at the total opening of the two wings of the valve or approaching the total opening. The absence of cavitation phenomenon was concluded in such cases and conditions.

Keywords: biomechanics, heart valve, BiMHV, finite element analysis.

I. INTRODUCTION

The human heart is the biological pump that moves blood throughout the circulatory system. It is essential for living and, therefore, is important that it functions correctly throughout a person's lifetime. Components of the heart include the four main compartments (two atrium and two ventricles) and the heart valves [1]. For various causes such as heart valve diseases including valvular stenosis and insufficiency. Valve failure can occur leading to the need for valve replacement. This occurs mostly in the aortic and mitral valves, making up 95% of replaced valves [2]. Prosthetic valves fall into one of two categories, Mechanical heart valves (MHVs), in which the valve is constructed using artificial materials [3], and Bioprosthetic heart valves, which use tissue from animal or human sources to replace defective native valves [4]. We can divide Artificial Heart valves into Mechanical Valves and Tissue (Biological) Valves. Mechanical valves as shown in Figure (1.1) are made from materials like titanium and carbon [3]. There are three main types of mechanical valve, namely caged-ball valve, tilting-disk valves and bileaflet valve, with many adjustments to these designs [4]. As shown in the figures below.

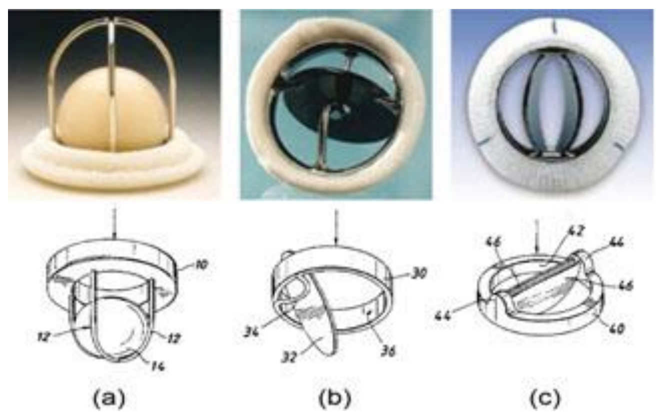

Figure1: Three kinds of mechanical valves; a) caged ball, b) tilting disc and c) bileaflet.

Bileaflet Valves have two semicircular leaflets retained inside the ring by hinges. The potential for obstruction of leaflets motion due to interference with cardiac structures is weak, as the open leaflets are positioned in the middle of the blood stream and enclosed within the ring in the closed positions [6]. Bileaflet Valves are widely used to substitute diseased native valves [11]. As seen in Figure (2).

The biological valves as one can see in Figure (1.3) include an enormous variety of devices. The bioprostheses contain the heterografts, consist of porcine (real valves of a pig) or bovine tissue valves (pericardium of a cow) and the allografts, which are preserved human aortic valve [13].

Figure 2: Tissue Valves [16].

Heart disease is becoming more common in our old age Valvular population. An estimate of the propagation from temperate to severe disease in patients<75 years old is 13.3% [10]. Valvular involvement by disease causes stenosis, insufficiency or both. Aortic stenosis is caused by narrowing of the orifice of the aortic heart valve (in varying degrees) and leads to obstruction of left ventricular outflow.

Previous in-vitro studies evaluated the performance and blood spoilage potential in BMHVs by quantifying parameters like velocity magnitude, Reynolds shear stresses and viscous shear stress from measured flow fields. In vitro LDV studies were conducted to evaluate the performance of various BMHV models [11]. Shipkowitz et al. used PIV and Computational Fluid Dynamics (CFD) to investigate how the opening angles of the (SJM) and (ATS) bileaflet valves affect their downstream flow characteristics. They concluded that the pivot region positioned farther upstream concerning the orifice trailing edge of the valve, provided a more favorable pressure distribution across the leaflet [12]. Yoganathan et al. notified that the profile of velocity right after the leaflets is non-flat with the top velocity of 2.2 m/s occurring in the lateral orifices. Also, the summit velocity in the main orifice midst of the leaflets is 2.0 m/s [13].

II. SCOP OF THE STUDY

In the present study A 2-D laminar, steady state, Newtonian finite element CFD model was used to investigate the influence of leaflet opening angle on the flow through bileaflet artificial heart valves [14]. And has been obtained the different results of velocity distribution, and pressure drops in each case. The velocity distributions and pressure drop of blood flow during bileaflet mechanical heart valve (SJM) were analyzed and investigated. In Aortic positions as represented in Figure (3).

Models of the mechanical heart valves are offered in this study describing steady, laminar and incompressible flow characteristics in a bileaflet aortic heart valves. The numerical method which was applied here, the Finite Element Method (Ansys v14). With two-Dimensional model of the Bileaflet artificial heart valves (SJM).

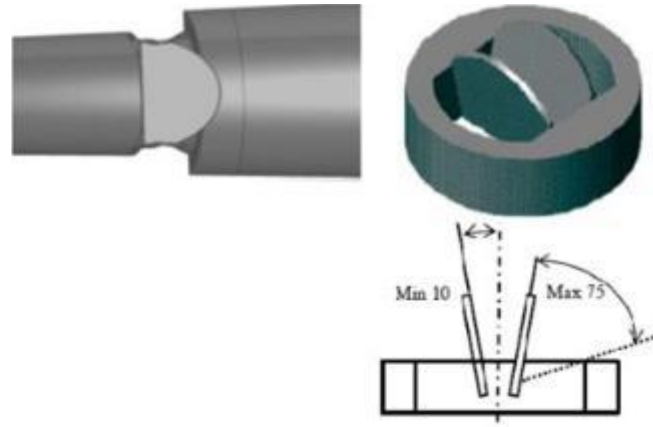

Figure 3: Aortic valve position.

III. MATERIALS AND METHODS

Analysis of the complex static and dynamic problems involves in essence three phases: selection of a mathematical model, the model analysis, and interpretation of the outcomes [15]. The major concept of FEA is to make calculations at only limited (finite) number of elements and then interpolate the results for the entire domain (surface or volume). Any continuous object has finite degrees of freedom and it is just not possible to solve the problem in this format. Finite element method decreases the degrees of freedom from infinite to finite with the assistance of discretization or meshing (nodes and elements) [16].

IV. STUDY OF THE VELOCITY DISTRIBUTIONS IN THE VALVE

The major issue in the current study was the velocity analysis of blood flow through the bileaflet artificial heart valve in three cases with different opening angles for the valve. Where we will get the knowledge of the highest velocity on Reynolds number and thus the sort of flow is laminar or turbulent, where the flow disorder will get the phenomena of clotting and this is the essence of this study. The analysis has been achieved by CFD method in Bileaflet heart valve designing process. Using Ansys v14.the kind of the analysis was static. According to, the inflow velocity boundary condition was (1m/s) as shown in Figure (4).

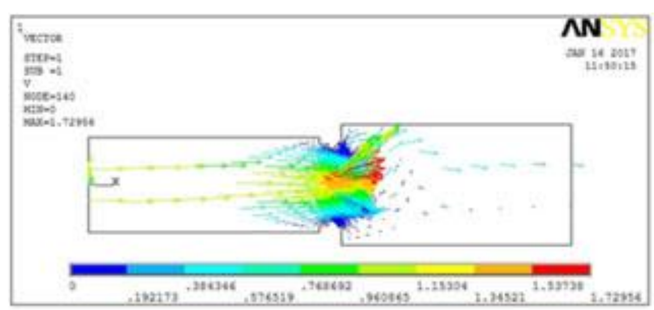

Figure 4: Velocity distribution of Bileaflet mechanical heart valve with opening angle equals to 63º.

V. GEOMETRICAL F.E MODEL OF BILEAFLET MECHANICAL HEART VALVES

The geometrical model used in this research is the simplified St. Jude Medical bileaflet artificial valve. The geometry of the mechanical heart valve and the artery wall used in this calculation as shown in Figure (5) the housing of the valves consists of an expanding tube with a diameter ratio of 1.3. The inlet diameter is 22mm, which results in an outlet diameter of 28mm [2]. The inlet and outlet channels are both 50 mm in length.

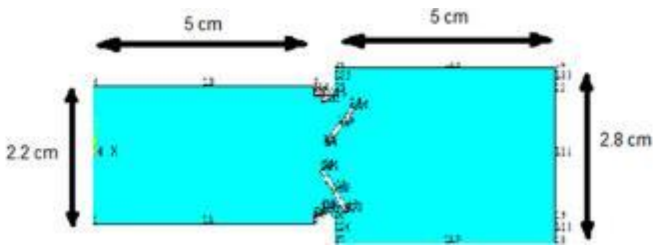

Figure 5: Sketch with dimensions

VI. SIMULATION

Simulation of blood flow through prepared models was proceeded by using Ansys v14 software. It was a steady, turbulent and Newtonian flow. K-epsilon model was used. For this study, the elasticity of vessel walls was ignored, valve and walls of aortic were assumed rigid. Models represent situations when disks are completely open [18].

VII. BLOOD MODEL

Blood was modeled as an isotropic, homogeneous, incompressible Newtonian liquid with the following parameters: density ρ = 1060 kg/m³, dynamic viscosity μ= 0.004 Pa.s. Which is representative of normal human blood properties at 37°C.

VIII. BOUNDARY CONDITIONS

The inlet velocity is conformable to cardiac output of 5 L/min and heart rate of 70 bpm with systolic stage duration of 0.3 s as illustrated in [19]. For the boundary conditions, constant velocity was considered as inlet condition (1m/s) and, zero static pressure was applied as outlet condition [20]. And no sliding condition was used at the solid walls and leaflets.

IX. GENERATE MESH

In the current study, the free meshing has been used. ANSYS method has a free meshing routine and it is easy to use. The free meshing is simple to create the geometry and meshing is fast. But disadvantage is that some triangular elements are used and some elements may have poor aspect ratios [21]. In this step, the number of nodes was (1667) and the number of elements was (1508), as represented in Figure (6).

Figure 6: Mesh Generation.

X. RESULTS AND DISCUSSION

A. Velocity Distribution

In the present study, these results which have been obtained for velocity distribution and pressure of blood flow through bileaflet mechanical heart valve where constant conditions were used for velocity and pressure at inlet, and outlet respectively (1m/s, 0 Pa). The target of this research was to analyze velocity distribution and investigate the drop pressure at constant boundary conditions. The outcomes were divided into three cases. Each case has various opening angles for the valve. The flow dynamic through these different kinds of opening angles valve under the conditions which was mentioned Previously, has been analyzed. The influence of each opening angle on blood flow components such as velocity field, vortices formation, turbulent density and cavitation has been investigated and it appeared that jet flow in velocity domain, turbulent intensity and Reynolds numbers have more effectiveness on platelet activation and as a consequence, on thrombus formation, than vortices formation. Then we saw that the pressure decreasing and cavitation phenomena would not occur in these cases.

The first one is the angle equal to 83°Figure (7). As one can see the velocity equal to v=1.35561m/s we calculated Reynolds number which is defined as:

$$Re = \rho UD/\mu \qquad (1)$$

Where ρ is the density of the fluid (kg/m³), U the velocity of the flow (m/s), D the diameter of the vessel (m), and μ the dynamic viscosity of the fluid (Pa. s). In this case Reynolds number is equal to 7903.2063 greater than 4000 so that it creates the turbulent flow. The existence of a large Reynolds number in the blood flow is one of the important agents of activation of platelets and thrombus forming. In the second one, when the angle is equal to 63° Figure (8) and as one can see the velocity= 1.72956 m/s we calculated Reynolds number, we found that Reynolds number is equal to 10083.3348>4000 so that it creates the turbulent flow. In the third one, when the angle is equal to 43° Figure (9) and as one can see the velocity=1.90558 m/s we calculated Reynolds number, also here we note that Reynolds number which equals 11109.5314> 4000 so that it creates the turbulent flow.

The best results were gained for models with a maximum valve opening angle =83° (near fully opening), for bileaflet valve. Bileaflet valves, unlike other valves generate symmetric blood flow. Two main streams on both sides of aorta, and one smaller in a center of the artery can be distinguished [18]. It can be assumed that this flow profile is better than asymmetrical flow generated by other kinds of valves, because it affects aortas walls equally, but still it is not analogous to the flow generated by natural heart valve, because in human valve the main stream is focused on the center of aorta. As represented on Figure (7) when the angle equals (83°), the maximum flow velocity generated by these valves was observed in the central fraction of the aorta. This is comparable to the flow through a natural human valve Moreover, for every valve, regardless of the type and disc position, in the area close to the valve ring very slow blood stream was observed. This is the area where platelet aggregation and thrombus forming are most likely to appear. Whereas in the other two angles (63°,43°) in Figures (8), and (9) the distribution of mean velocity comes to be variable in response.

In the current study and the most of previous studies, we noted that the extreme velocity through the centric orifice and the area of the recirculation range downstream of the valve leaflets decreased for an increase in opening angle. As the opening angle increased to 83° the maximum velocity through the central orifice increased and the maximum velocity midst the outer orifice decreased. We observed from the results that the distribution of symmetrical velocity in the situation of angle (83°), otherwise, the other two angles have less symmetry around the leaflets. Figure10 shows the curve of velocity distribution for the three angles under study. Table (1) below shows the values of each Reynolds number versus the velocity.

Table (1): The values of maximum Velocities and Reynolds numbers

Velocity	1.35561	1.72956	1.90558
Re	7903.2063	10083.3348	11109.5314

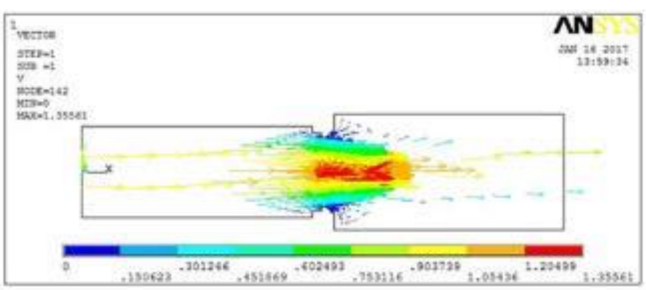

Figure 7: Total Angle 83º.

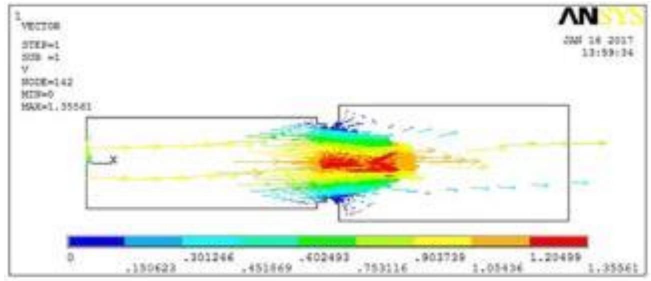

Figure 8: Total Angle 63º.

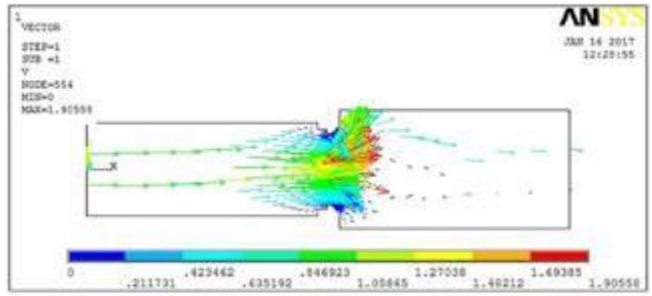

Figure 9: Total Angle 43°.

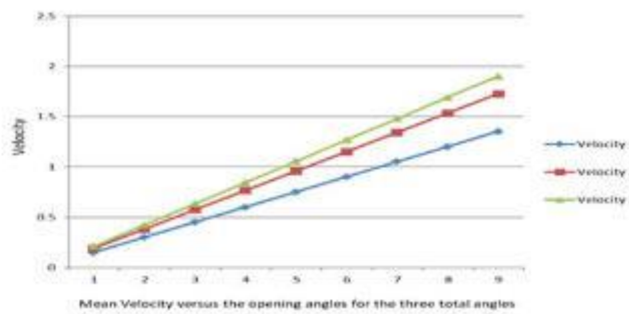

Figure 10: Mean Velocity versus the opening angles for the 3 total angles velocity1 (83°), velocity2 (63°), velocity3 (43°)

B. PRESSURE DROP

Cavitation is the formations of vaporous or gaseous bubbles in fluids. It is similar to boiling except that bubbles are formed as a result of decrease in pressure instead of an increase in temperature.

The results which have been recorded include values of pressure to study the extent of cavitation phenomena in these valves or not. Where the cavitation can appear in regions of high velocity that are characterized by large pressure drops during the closure of the valve [22]. Figures (11), (12), and (13) show the static pressure contours for the entire field for various opening angles of valves at the constant inlet velocity equalize to 1 m/s. As one can see the minimum blood static pressure, in the worst is not less than -984.659 Pascal (-7.4mmHg). By considering the pressure of vapor of the human blood (-613 mmHg) [21]. It can be discovered that cavitation will not occur in each case. So cavitation phenomena do not menace the valves. We have to know that any increase/decrease in the velocity within the valve leads to decrease or increase in the static pressure and vice versa. Also, a reduction in kinetic energy leads to raise in static pressure. The computationally predicted valve pressure gradients (Fig.13) show that the high pressure was 1985.7Pa (14.9 mmHg) when the opening angle is equal to 43°. And (Fig.11) shows that the low pressure was 616.742Pa (4.6 mmHg) when the opening angle is equal to 83°. And Figure (14) shows the pressure distributions at three different opening angles.

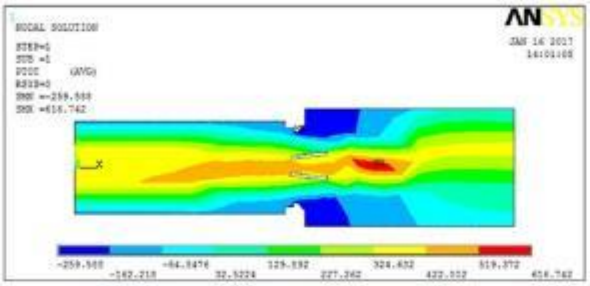

Figure 11: Total Angle 83°

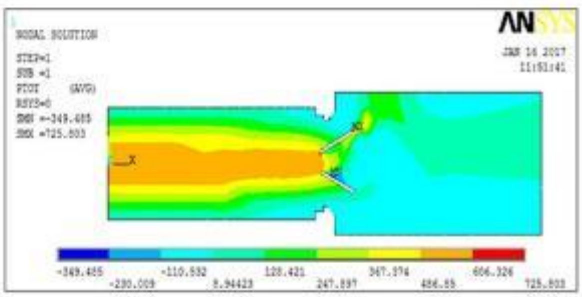

Figure 12: Total Angle 63°.

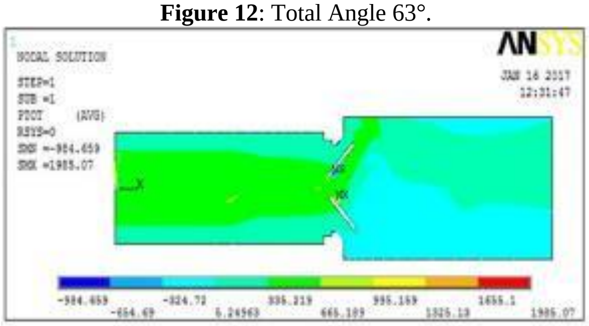

Figure 13: Total Angle 43°.

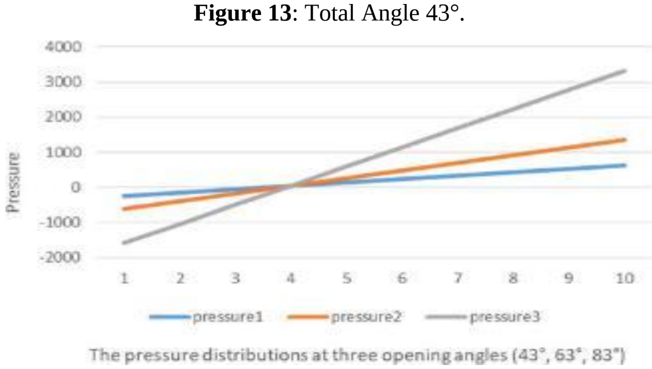

Figure 14: The pressure distributions at three opening angles 83°, 63° and 43°.

XI. Conclusion

The results which have been found confirmed that when the opening angle degree is near from fully opening then the flow is similar to natural flow throughout the heart valve, and vice versa. The study emphasized that the larger the opening angle, the better the flow distribution. And about the cavitation phenomenon, the results identified showed that, this phenomenon does not occur in this type of valve, and under these conditions.

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