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An Investıgation of the Left Ventrıcle of Human Heart by Fluıd-Dynamıcs Modelıng

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ABSTRACT

In this study an echocardiography device in Azadi Scientific Hospital of Duhok, Kurdistan - Iraq has been used to mesure the Left Ventricle (LV) wall thickness of three Patient groups: control (19 patients), smoking (15 patients) and asthma (9 patients) using a simulation method based on Computational Fluid Dynamics (CFD). The study is based on the design of a computational model of the human Left Ventricle using specific data (IVSd, LVIDd, LVPWd, IVSs, LVIDs and LVPWs) taken from the 2D M-mode echocardiography of selected groups. However, the phase diastole data are used to simulate blood flow inside LV by ANSYS FLUENT V14 based on CFD technology and the information have been used to build a numerical mesh for CFD simulation which provides detail 2D LV velocity and pressure distributions in the LV cavity. Finally, the data for the three groups are analyzed by SPSS V1 to observe how the diseases can affect on the LV two phases (systole and diastole) parameters. The effects of the diseases (asthma, smoking and control), of the Age , of the Sex and of the Body Mass Index (BMI) have been observed.

Keywords: *Computational Fluid Dynamics (CFD), LV modeling, ANSYS FLUENT V14,M-mode echo, Asthma, Smoking, LVwall thickness .*

Introduction

Heart is one of the most important organs located in the chest of human body, located just behind and slightly left of the breastbone. The heart consists of four chambers, the two upper atria and the two lower ventricles. The Left Ventricle is the strongest chamber pumps blood with rich oxygen to the rest of the body. However, the cardiac cycle is divided into two main phases; the diastole which is the ventricular filling phase, and the systole that is the ventricular contraction phase as seen in Fig 1.[1].

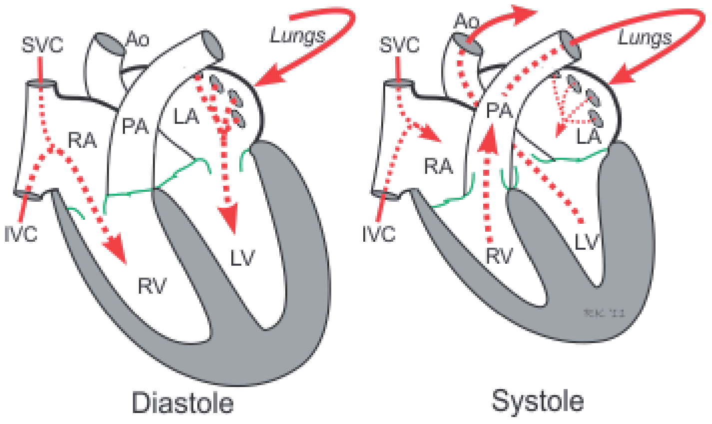

Figure 1. Two main phases of cardiac cycle: the diastole and the systole phases [2]

The left ventricle is one of four chambers of the heart. It is located in the bottom left portion of the heart below the left atrium, separated by the mitral valve [3]. In the diastole phase, the heart ventricles are relaxed and the heart fills with blood. In the systole phase, the ventricles contract and pump blood into the arteries. The fourth heart sound is a soft sound due to an increase in the ventricular pressure following an atrial systole. The pressure-based coupled algorithm is an important milestone in the development of the FLUENT solver, as it provides the user with a modern, fully coupled solution approach that is suitable for a wide range of flows [4 & 5]. Kronik *et al.* Arnett et al., Kühl *et al.* and Gottdiener *et al.* [6,7 and 8] defined M-mode images which are a continuous 1-dimensional graphic display and can be derived by selecting any of the individual sector lines from which a 2D image is constructed. M-mode echocardiography is used to estimate chamber volumes and Left Ventricular (LV) mass when those structures are geometrically uniform.

Long *et al.* [9] demonstrated a subject specific approach for simulating blood flow within a LV by a combined analysis of Computational Fluid Dynamics (CFD) and Magnetic Resonance Imaging (MRI). The Navier-Stokes equations for 3D time-dependent laminar flow with moving walls were solved using a finite-volume based CFD solver CFX4. Furthermore, Khalafv and *et al.* [10] demonstrated a quantitative assessment of LV conditions in normal and patients with myocardial infarction using ANSYS-CFX 12 version. The study seems to provide useful information on intra-LV flow velocity and pressure drops with diverse heart diseases. The streamlines obtained in the 2D model indicate the main characteristics of flows produced in the left ventricle. It is also believed that the pressure–flow relationship of the 2D model is a good indication for the 3D model. Malvè *et al.* [11] assumed that the blood density was taken as 1050 kg/m^3 and a blood viscosity of 0.003528 Pa, and the blood flow was assumed laminar and incompressible under unsteady flow conditions.

Su *et al.* [12] modeled left ventricle in two-dimension (2D) with both mitral and aortic valves integrated. In both sexes the duration of smoking increases by the number of cigarettes smoked daily; smoking 1–4 cigarettes per day was associated with a significantly higher risk of dying from ischaemic heart disease and from all causes, and from lung cancer in women. In both sexes there is an increase in serum total cholesterol and serum triglycerides by cigarette consumption, while there is a decrease in physical activity during leisure [13]. The applications of CFD in bio-medical problems are based on modeling the flow of blood in the heart and vessels [14].

Finite element analysis is a method for numerical solution of field problems, initially it was used in the field of structural mechanics [15], and ANSYS is a general-purpose finite-element modeling package for numerically solving a wide variety of mechanical problems. These problems include static/dynamic, structural analysis (both linear and nonlinear), heat transfer, and fluid problems, as well as acoustic and electromagnetic problems [16].

In general, a finite-element solution is divided into the following three stages:

A. *Preprocessing:* Defining the problem and the major steps in preprocessing.
B. *Solution:* Assigning loads, constraints, and solving.
C. *Post processing:* further processing and viewing of the results. In this stage one may wish to see (a) velocity contour diagrams. (b) Pressure contour diagrams.

ANSYS FLUENT is newest computer program for modeling fluid flow, heat transfer, and chemical reactions in complex geometrics. The program solves conservation equations for mass and momentum which is called Navier-Stokes equations.

These equations are complemented by algebraic relations such as the equation of state for compressible flow. For example, Navier-Stokes and continuity equations for modeling fluid motion, which can be two dimensional/three dimensional, unsteady and compressible flow:

$$\rho\frac{\partial u}{\partial t} + \rho u\,\frac{\partial u}{\partial x} + \rho v\,\frac{\partial u}{\partial y} = -\frac{\partial \hat{P}}{\partial x} + \mu\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right] \quad (2.1)$$

$$\rho\frac{\partial v}{\partial t} + \rho u\,\frac{\partial v}{\partial x} + \rho v\,\frac{\partial v}{\partial y} = -\frac{\partial \hat{P}}{\partial y} + \mu\left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right] \quad (2.3)$$

$$\rho\frac{\partial w}{\partial t} + \rho u\,\frac{\partial w}{\partial x} + \rho v\,\frac{\partial w}{\partial y} = -\frac{\partial \hat{P}}{\partial z} + \mu\left[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right] \quad (2.4)$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (2.5)$$

where ρ = fluid density, u and v are fluid velocities in x, y directions respectively, P is pressure and μ is dynamic viscosity.

In addition, there are two numerical methods in the ANSYS FLUENT:

• Pressure-based solver
• Density-based solver

The pressure-based approach is used for low-speed incompressible flows, while the density-based approach is mainly used for high-speed compressible flows. For the present study Pressure-based solver is used.

The main purpose of this thesis is to investigate the effects of asthma and smoking diseases on the Left Ventricle parameters by comparing a control group of patients using CFD method. In order to develop this procedure, the data of echocardiography of three patient groups (asthma, smoking and control) have first been taken from in the cardiology department of Azadi scientific hospital of Duhok in Kurdistan of Iraq. The velocity and pressure gradient of blood flow distribution inside a 2-D LV model for the three groups have been simulated using ANSYS FLUENT -V14. The results have been analyzed statistically by using the SPSS software, 2001 for Windows. Finally, the velocity and pressure of blood between the Control, Smoking and Asthma subjects are compared with each other.

Materials and Methods

This study was carried out during three months of April, June and July 2013 in Scientific Azadi Hospital, General Cardiology department in Duhok City in Kurdistan of Iraq. All the subjects in this study, who are the patients in the Cardiology department, are divided into three groups (or cases) as control, smoking, and asthma. The detail of three cases, i.e. Case I, Case II and Case III, are presented in Table 1

Table 1. The patients and their properties

Groups	Male(ages/yr)	Female(ages/yr)	BMI(kg/m^2)	Total
CaseI(Control)	10 (18yr-60yr)	9 (25 yr- 80 yr)	(18.37- 31.11)male (22.22-9.54)female	19
CaseII(smoking)	10 (19yr-59yr)	5 (33 yr- 57 yr)	(19.37- 29.03)male (24.22-8.58)female	15
CaseIII (asthma)	-----------	9 (33 yr- 90 yr)	(24.22- 41.52)	9

Here it should be noted that Body Mass Index (BMI) was calculated as weight in kilograms divided by the square of height in meters (kg/m^2) [17].

Since the main aim of the study is to examine the pressure gradient and velocity of blood flow inside LV we need the data of left ventricle wall thickness of all the subjects. LV Wall thickness of the subjects has been measured by M-mode 2D echocardiography method, all the parameters have been noted such as Inter Ventricular Septum thickness wall at the end of diastole and systole (IVSd and IVSs), Left entricular internal diameter at the end of diastole and systole (LVIDd and LVIDs), Left Ventricular Posterior Wall thickness at the end diastole and systole (LVPWTd and LVPWTs)), have been measured in cm.

Application of ANSYS FLUENT Method

In this section in order to examine the pressure gradient and velocity of blood flow inside left ventrical of human heart, we are going to apply the data of three cases measured by M-mode echocardiography given before to LV modeling run by ANSYS V.14 simulation program, for which one follows three main steps in a typical ANSYS analysis as below [18]:

1. Modeling: This involves (Simplification, idealizations), (Material Definition and it is properties), (Meshing), respectively.
2. Solution: (Loading and supporting condition), (Getting the solution).
3. Review results: (Plot/list results).

CFD is based on M-mode echocardiography in practical real patient.

Geometry and Boundary Conditions

One of the main material in simulation is blood, which is assumed to be an incompressible, homogeneous and Newtonian fluid, and the viscosity is 0.0035 Pa.s and the density is 1050 kg/m^3. The other material is related to the property of wall of LV. For example, it should have a hyper elastic material wall with a density of (1366) kg/m^3 [15, 16, 19 and 20].

The LV wall has no slip boundary conditions at the fluid-solid interface [21 and 22]. The blood flow was characterized by rapidly accelerated and decelerated laminar and transient flow with moving boundaries [22,23,24,25,26,27 and 28]. The domain was solved using second-order upwind scheme.

Statistical Analysis

All data has been analyzed using the Statistical Package for Social Science SPSS 1 windows compatible computer. Level of statistical signification was determined according to the Duncan Groping test multiple ranges at level set as $\leq$ 0.05. Descriptive data were expressed with use of means values with the same or different letters.

Results and Discussion

In this section we present the results of the calculations and discuss the effects of diseases (smoking and asthma) on LV human heart parameters. The effects of smoking and asthma together with the control group, which are statistically analyzed, are presented and compared to each other on a table. In particular, the results of Left Ventrical wall thickness of human heart data or six parameters, which are LVIDs, LVIDd, IVSs, IVSd, LVWTs, and LVWTd, for the three cases are illustrated in the figures, and the correlation values of the six parameters between the LV wall thickness are discussed.

As seen in Table 2, the statistic analysis of Smoking and Asthma effects on Left Ventricle parameters has been displayed in Table 2. The results indicate that the six parameters of the groups has been compared to each other. It can be seen that the mean of IVSd for the smoking and asthma in the first column increased to that of the control group. On the other hand, the second column shows a comparison of LVIDd of the smoking and asthma subjects with the control subjects, where the mean value of the smoking and asthma slightly decreased to the control, which is not statistically significant. The third column shows a comparison of LVPWd values. A significant difference between the smoking group and the control can be seen while the asthma and control subjectsis non-significant. However, there is also no- significant difference between the smoking and asthma and the control groups in the 4th and 5th columns. In particular, one can see an obvious difference as the smoking and asthma groups are compared to the control groups in the sixth column.

Table 2. Mean values of Left Ventricle parameters (IVSd, LVIDd, LVPWd, IVSs, LVIDs and LVPWs) for the three Cases, Means with the same letter are not significantly different.

Disease	IVSd(cm)	LVIDd(cm)	LVPWd(cm)	IVSs(cm)	LVIDs(cm)	LVPWs(cm)
	Mean	Mean	Mean	Mean	Mean	Mean
Control	0.96b	4.48b	1.3a	1.48a	2.95b	1.53a
Smoking	1.31a	4.35b	1.21b	1.49a	3.01b	0.35b
Asthma	1.14a	4.28b	1.26a	1.37a	2.83b	0.35b

Moreover, the variation of these six parameters with respect to female Ages for these three cases have been illustrated in detail in the figures given below. For example, Figure 2. shows the relation between the Age and the Left Ventricle Posterior Wall thickness in systole (LVPWs) for female Smoking and Asthma subjects compare to the female of control patient. The figure shows that the LVPWs for the control are much greater than the left ventricle posterior wall thickness in systole for smoking. The relation between the Age and the Left Ventricle Internal Diameter in systole (LVIDs) for female of the smoking and asthma to the female of the control patients are plotted in Figure 2. The LVIDs at (33,50) point converge together for female of control, smoking and asthma.

Figure 3. displays the relation between the female ages for Smoking and Asthma subjects with the female of control and all their effect on the Inter Ventricular Septum in Systole (IVSs) is displayed in Figure 4. which shows that the IVSs at age 33 years for control patient is greater than IVSs for smoking and asthma patient, and shows the similarity of IVSs in (53, 57, 87 and 90) years for control and asthma patient. On the other hand, the IVSs is diverge in age (38, 40, 46 and 50) years.

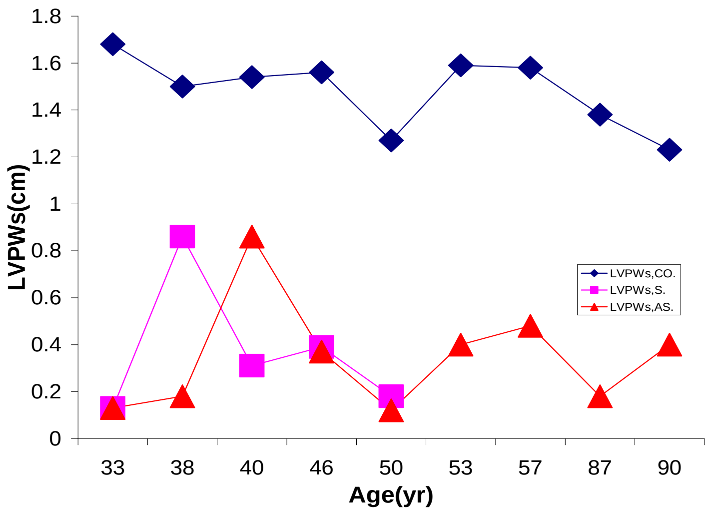

Figure 2. The trend of the dependence Left Ventricle Posterior Wall in systolic (LVPWs) on Age in the femal human cardiac (control, asthma and smoking).

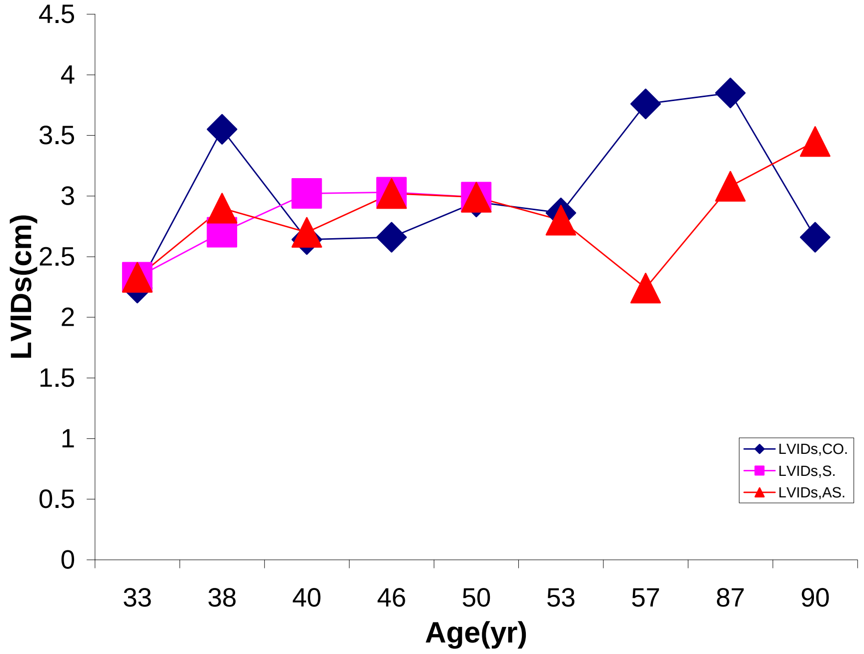

Figure 3. The trend of the dependence Left Ventricle Internal Diameter in systolic (LVIDs) on Age in the femal human cardiac (control, asthma and smoking)

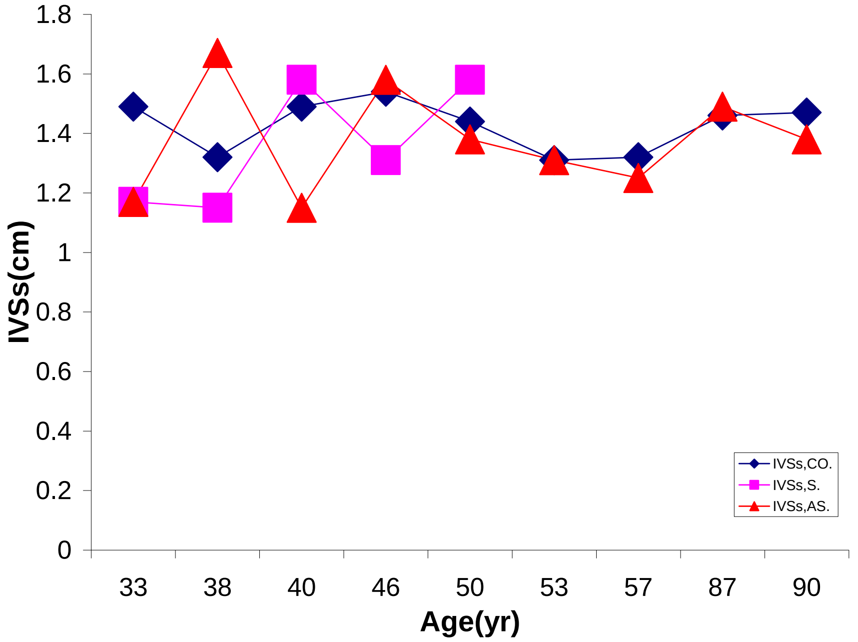

Figure 4. The trend of the dependence Inter Ventricular Septum in systole (IVSs) on Age in the femal human cardiac (control, asthma and smoking)

The relation between the female ages for Smoking and Asthma subjects with the female of control and all their effects on the Left Ventricle Posterior Wall in diastole (LVPWd) is displayed in Figure 5. The LVPWd is converged for control, smoking, and asthma subjects at age (33, 46, 53 & 90) years, and it is similar at age (38, 40, 50, 57 and 87) year. Figure 6. depicts the relation between the female ages for Smoking and Asthma subjects with the female of control and all their effects on the Left Ventricle Internal Diameter in diastolic (LVIDd) which converged at age (50 and 87) years and diverged at age (33, 53, 57 and 90) years.

Figure 7. displays the relation between the female ages for Smoking and Asthma subjects with the female of control and all their effects on the Inter Ventricular Septum in diastole (IVSd) which show that the value of IVSd for control subject is less than the other two cases, but IVSd for Smoking is greater than Asthma and Control in age 38, 40, 46 and 50 year.

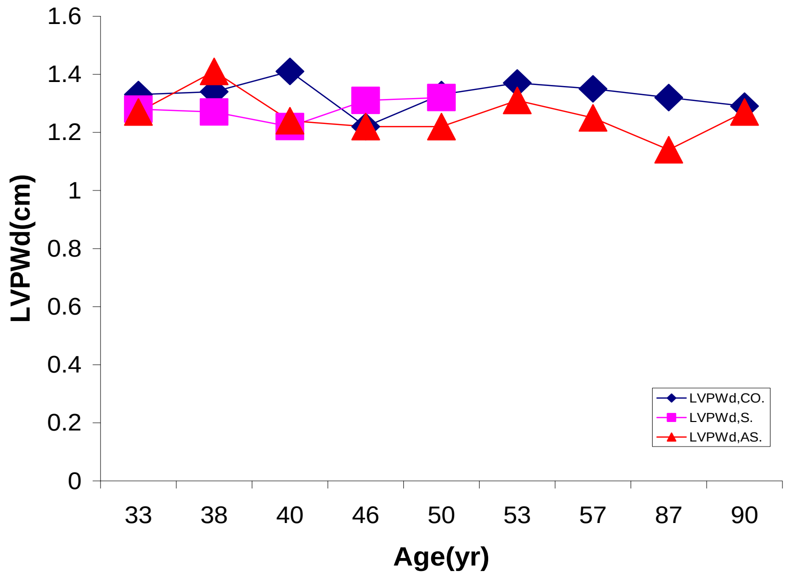

Figure 5. The trend of the dependence Left Ventricle Posterior Wall in diastolic (LVPWd) on Age in the femal human cardiac (control, asthma and smoking).

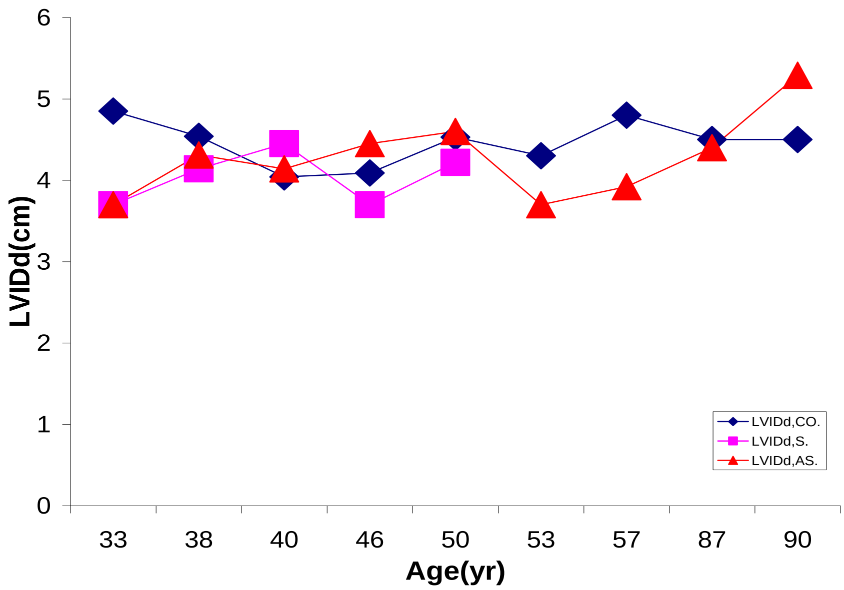

Figure 6. The trend of the dependence Left Ventricle Internal Diameter in diastolic (LVIDd) on Age in the femal human cardiac (control, asthma and smoking)

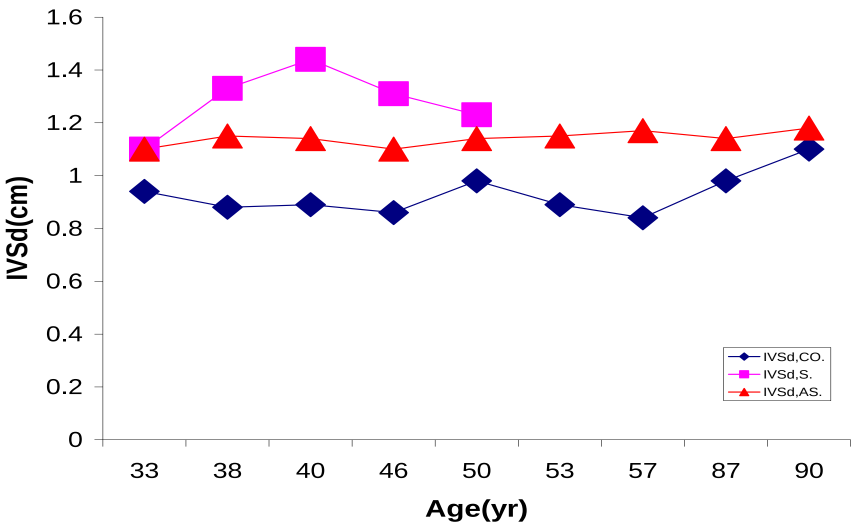

Figure 7. The trend of the dependence Inter Ventricular Septum in diastole (IVSd) on Age in the femal human cardiac (control, asthma and smoking)

The simulation of the velocity and pressure distribution inside LV for the three cases was carried out using ANSYS and Fluent (ANSYS Fluent14) program. The model used in the calculations is based on mitral valve opened and aortic valve closed [29, 30 ,31,32,33,34,35,36 and 37], and presents the streamlines at the onset of diastole with colors for velocity magnitude. It is worth of noting that the movement of the mitral valve was not modeled in the present study but the blood flow at the mitral valve was modeled as a bell mouth inlet. The blood entered into the LV from the mitral orifice and rapidly filling phase began. The final steps for filling LV with blood as illustrated in the figures given below. The velocity streamline in mitral valve region is much greater as compared to the other regions, which can be seen in the figures.

Let us now analysis the results in the figures. Figure 8. illustrates 5 times step for blood flow inside the LV from the onset of diastole to the peak of diastole. However, we must note that the average values of Inter Ventricular Septum in diastole (IVSd), Left Ventricle Internal Diameter in diastolic (LVIDd) and Left Ventricle Posterior Wall in diastolic (LVPWd) have been taken from the practical data of real control patients given in Table 2. These three parameters have been applied respectively to wall thickness of the control patients, i.e. case 1. This model shows the streamline velocity at the base (near the mitral valve region) of LV, which is greater than the streamlines in the mid-wall and apical LV. The results indicated that a strong clockwise vortex was developed near the junction of aortic valves. According to (S.S. Khalafv et.al.2012), who also found the similar streamline velocity using CFX 12 for modeling LV, the streamline velocity in mitral valve region is greater than the others in agreement with our results. Moreover, the results indicated that a strong clockwise vortex was developed near the junction of aortic and mitral valves.

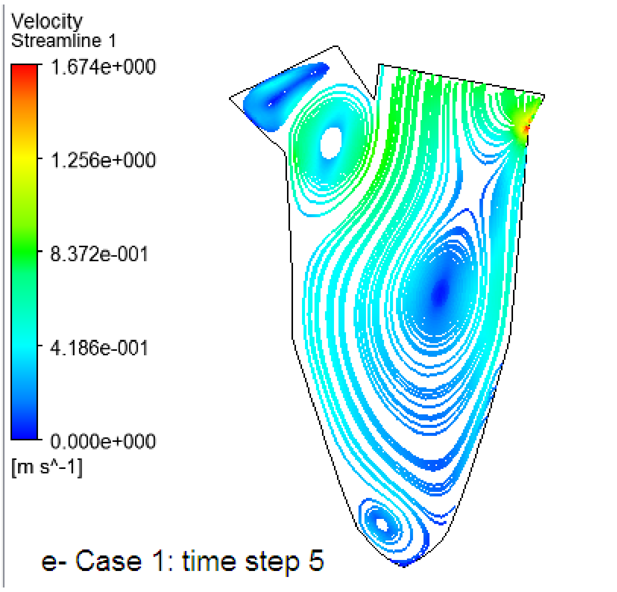

Figure 8. Streamlines at the onset of diastole indicate the peak of diastole for the control patient, case1; streamlines colored by velocity magnitude.

velocity at the base (near the mitral valve region) of LV is greater than the streamlines in the med wall and apical LV. The results indicated that a strong clockwise vortex was developed near the junction of aortic valves.

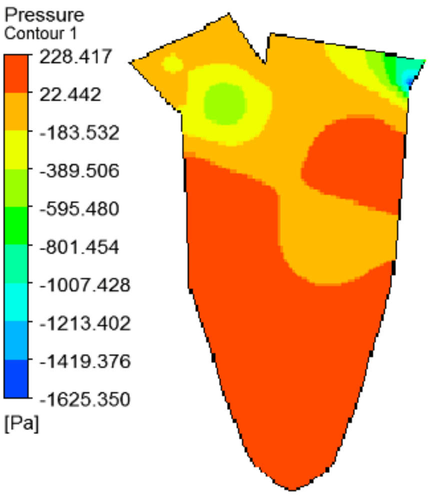

Figure 9. Pressure contour of simulated flow through a closed aortic valve for case1

As can be seen in Figure 9. that the pressure gradient in the apex and the septum is greater than the that in the base of LV for the case1 (the control) as seen in the contour.

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