Determination of aortic valve efficiency through vortex physical parameters in normal, regurgitate, and stenotic valve by using Doppler-mode echocardiography

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Abstract

Background and objective: Doppler ultrasound technique has been proposed as a noninvasive means of quantifying diastolic and systolic cardiac function by measuring flow propagation into the left ventricle and ejection blood to the body. The relationship between Doppler-derived parameters and underlying fluid dynamics is still unclear.

Methods: The purpose of this study is to deduce effective physical parameters used in measuring the change in the geometrical shapes of the aortic valve leaflets during the vortex formation. These parameters are defined as the “Blockage factor, Strouhal number and Formation number”. One hundred fifty subjects were selected; The B-factor was correlated with Strouhal number and Formation number for 100 normal aortic valve subjects, and 50 abnormal subjects divided equally into regurgitate (25), and stenotic aortic valve (25), other physical parameters are also calculated. Doppler Echocardiography technique as a noninvasive technique that provides unique hemodynamic information which can not be achieved by any other means.

Results: The accuracy of the results depends, however, on meticulous technique and an understanding of Doppler principles and flow dynamics. This technique recommended through scientific literature. It has been found that the mean values and standard deviation of (ST-No) and (F-No) for normal aortic valve are (l.55 ± 0.55) and (10.12 ± 3.16), regurgitate (2.823± 0.992) and (5.722± 1.68), and for stenotic aortic valve subjects are (0.939± 0.14) and (l5.82± 2.20) respectively.

Conclusion: The results show that (St-No) of normal aortic valve is larger than that for stenotic, which may indicate that the inertial effects of normal valve are larger than those of stenotic valve. This because pressure energy is expanded to overcome inertia rather than converted solely to kinetic energy. The results obtained showed significant elevation of (ST -No) with aortic valve dimensions, and the improvement in efficiency decreases with increasing Strouhal number. A significant elevated (F-No) has been also noted to be increased with aortic valve area. The study of the Formation number and Strouhal number' is important to determine the severity of the stenotic and regurgitate aortic valve and gives a good parameters that can be used in medical diagnosis.

Keywords: Echocardiography, hemodynamic, blood vortices, vortex indices.

Introduction

Vortex is a spinning turbulent flow with closed streamlines. Flow fields with vortices, which concentrated in a district region have been observed in many fluids. Many of these flow fields are very complex, involving body forces, energy sources, compressibility and real gas effects.

Blood flow into ventricular chamber is a good example. Human heart plays a vital part in cardiovascular physiology, functioning as a pump to supply blood to the entire circulatory system.Detailed hemodynamic information a bout the left ventricle and aorta can enhance our understanding of

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physiological function of the heart; also it can be very useful for certain clinical treatments [1]. Many studies have been conducted to understand the spatial resolution of the flow pattern in left ventricle. But, the highly unsteady involvements, large deformation of (LV) chamber wall and valves through diastole and systole made this flow un understood yet. Ultrasonography (Diagnostic sonography is an ultrasound-based diagnostic imaging technique used for visualizing subcutaneous body structures including tendons, muscles, joints, vessels and internal organs for possible pathology or lesions), Echo Doppler (An echo Doppler is a medical test in which high frequency sound waves are transmitted into the heart to detect its shape, size, and motion. The sound waves are transmitted from a microphone that is placed over the chest. As the sound waves bounce off the structures of the heart, they are captured and turned into images that are displayed on a monitor screen.), and Magnetic Resonance Imaging (is a medical imaging technique used in radiology to visualize internal structures of the body in detail. MRI makes use of the property of nuclear magnetic resonance (NMR) to image nuclei of atoms inside the body.). These techniques may offer non-invasive, anatomically accurate, time-matching structure of the heart chambers but the modes is usually two-dimensional views .of the three-dimensional phenomena. Therefore we propose to use Computational Fluid Dynamics technique to derive an understanding of the time resolved aortic flow in fully three dimensions. The ventricular filling created by the trans-aortic pressure gradient that develops during early diastole can be represented as a round jet from orifice with the same dimensions as the aortic valve. We believe that such vortex rings play an important role in ventricular filling changing shear conditions, stagnant regions and conversion of kinetic energy into pressure, etc. Vortex can be any circular or rotary flow that possesses vortices [2]. Vortex rings have been studied for more than a century. Reynolds appears to have been the first to observe correctly the flow field of a real vortex ring, , and to note that the ring grows in size and slows down as it entrains the surrounding fluid. Since then considerable effort has been invested in this field in an effort to understand the evolution and the dynamics of the flow structure [3]. A vortex ring is formed by imparting an ax-symmetric impulse to a fluid. Past experimental studies [4, 5] have been established that the vortices layers leaving the orifice of the jet and becomes unstable forming Kelvin-Helmholtz waves and then rolls up into vortex rings that are carried downstream where they become three dimensional and eventually break down. In addition to vortex rings, there is a significant evidence of stream wise structure, near both vortex cores and the regions between successive vortex cores in the shear layer called braids. Experiments by Lasheras and Maxworthy[6], and numerical computations by Martin and Meiburg [7] illustrate the role of shearing forces acting perpendicular to the jet axis in the evolution of stream wise vortices in the braid region [8, 9]. During literature review, it has been found that some physical parameters are vital to diagnose quantitatively the ability of heart and some main valves (in this study aortic valve (normal, stenotic, and regurgitate) efficiency and to determine, blood flow vortex formation process, Strouhal, and Formation numbers, and Block factors, by using Doppler-Mode Echocardiography.

Methods

A- Participants of the project:

Throughout the period of the study, which lasted for about one year, 150 Participants, were selected from a large number of people were referred to units of Echocardiography in Al-Yarmouk Teaching Hospital (Baghdad), and Rizgary Teaching Hospital (Erbil). Some of the Participants were of normal heart others are suspected of aortic valve prolapsed, but they are mostly referred for a completely different reasons like ischemic heart disease, left ventricular hypertrophy, ventricular and atria septal defects, myocardial infarction, mitral stenosis, or any other disease that was suspected by other physical examination like the stethoscope, electrocardiography (ECG), X-ray, blood pressure and so on. The selected individuals were divided into three groups according to the results of the aortic valve dimension, which were reported by (Mahboba M.H et al 1998) [10], and as follows:

1) Normal group subjects (100) who have aortic valve dimension (Dcm) (> 1.5 - 2.6 cm).
2) Regurgitate aortic valve of dimension (Dcm > 2.6 cm), 25 people.
3) Stenotic aortic valve group subjects of valve dimension (Dcm ≤ 1.5 cm), 25 people.

B- Vortex Flow Meters:

The forming vortex appears to reach saturation at nearly the same non-dimensional time if the initial acceleration or final Reynolds number (is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions). This led to the notion of a characteristic formation time, a natural pacemaker in the system dictating when saturation begins. For the vortex ring, the critical time is approximately four diameters, where time (t*) is measured in terms of the average velocity of the generator and its diameter; this definition seems to be the same as the stroke ratio of the generator (ratio of the distance the generator travels divided by its diameter) [11, 12];

$t^* = U\,t / D = L/D$ (1)

Where (t*) is the vortex formation time, measured in terms of the average velocity of blood (U) of the generator, (t) time interval of the average velocity jet, and (D) is the diameter of the valve, and (L I D) is the ratio of the distance the generator travels (U t) divided by its diameter (D). Strouhal number (ST-No): is in fact set by the vortex formation time. Therefore understanding the timing of the vortex formation process can be the way to understand why the Strouhal number is so remarkably constant, even across different geometries and wide ranges of Reynolds number [13, 14].

(ST-No) = 1 / t* or = D/Ut (2)

The value of the Strouhal Number is related to the vortex formation process and its reflections as a kinematics parameter that has a strong effect on the hydrodynamic of the fluids, which can be seen in equation (3) which shows the relationship between the vortex frequency and fluid velocity [13, 14].

(ST-No) = f D / V ………(3)

Where (f bets/sec) represent the vortex frequency, (D. cm) represents the width of the bluff body, and (V. cm/sec) represents the average of fluid velocity. Some researchers tried to apply the concept of Strouhal Number, in equation (3) Where (f = bets/sec) is the heart rate, (D cm) is the aortic valve diameter, and (V cm/sec) the maximum velocity during systole, in order to characterize the dynamic of the filling process of the left ventricle[4, 15]. Formation number (F-No): It is the physical parameter that can be demonstrated the dynamic of the vortex roll-up process which is a non-dimensional time scale based on the E--wave period. This parameter is given by the following equation[2]:

(F-No)=TU/D ………… (4)

Where (T sec.} is the filling period (E-wave), (U cm/sec.) is the average velocity for the filling period and (D cm) is the aortic valve annulus.

This (F-No) is different in its nature from the Strouhal Number, where the time scale is the frequency of occurrence rather than the period of the event.

Block factor (B.F): is defined as the effective area of the aortic valve divided by the full- born area of the valve, and is given by the equation (5).

B .F = V. (ST- No) / f. D …………..(5)

Where: (f) is the heart frequency (beat/sec), (D) is the aortic valve diameter (cm) and, V is the mean velocity (cm/sec) for the ejection phase.

Results

Determination of vortex physical parameters for heart chambers and the valves are the quantitative measures of their efficiencies. The aim of this project was to measure some of the physical parameters such as Strouhal number (ST-No), and Formation number. This work has been reached these goals in drawing calibration curves which have been suited for three groups of subjects: I- Normal aortic valve subjects, (NAV, D = (> 1.5 - 2.6 cm) 100 volunteers.

II- Stenotic aortic valve, SAV, D= ((Dcm ≤ 1.5 cm) 25 patients.

III- Regurgitate aortic valve, D= (Dcm > 2.6 cm), 25 patients

The Vortex Physical Parameters (the vortex formation time, *t, the Strouhal number (ST-No), the formation number (F-No), and the Strouhal number (ST-No) with relation to heart frequency have been calculated from equations (1, 2, 3, and 4 respectively). The results of curve fitting behavior for these parameters versus the diameter of aortic valve for the three groups are;

I- Normal subjects group, the behavior respectively are in figures (1 – a, b, c, and d) in which the fitting equations (1.a – 1.d) are;

y = 52.942e--0.8327x ……… (1 - a)
y = 0.0189e 0.8327x ………. (1 - b)
y = 52.942e -0.8327x ………. (1 - c)
y = 0.0056e 0.7243x ……… (1 - d)

II – Stenotic aortic valve subjects group, the behavior respectively are in figures (2 – a, b, c, and d) in which the fitting equations (2.a – 2.d) are;

y = -113.88x2 + 304 x - 186.49 … (2 - a)
y = 0.4874 x2 - 1.2987x + 0.927 ... (2 - b)
y = -113.88 x2 + 304 x - 186.49 ... (2 - c)
y = 0.0302 x2 - 0.0806 x + 0.0693 .. (2 - d)

III- and for regurgitate aortic valve subjects group, the behavior respectively are in figures (3 – a, b, c, and d) in which the fitting equations (3.a – 3.d) are;

y = - 9.4349 x + 31.566 …. ……. (3 - a)
y = 0.001e 1.9093 x ………… (3 - b)
y = 1019.1e - 1.9093 x ………… (3 - c)
y = 7E-05 e 2.3707 x ……………(3 - d)

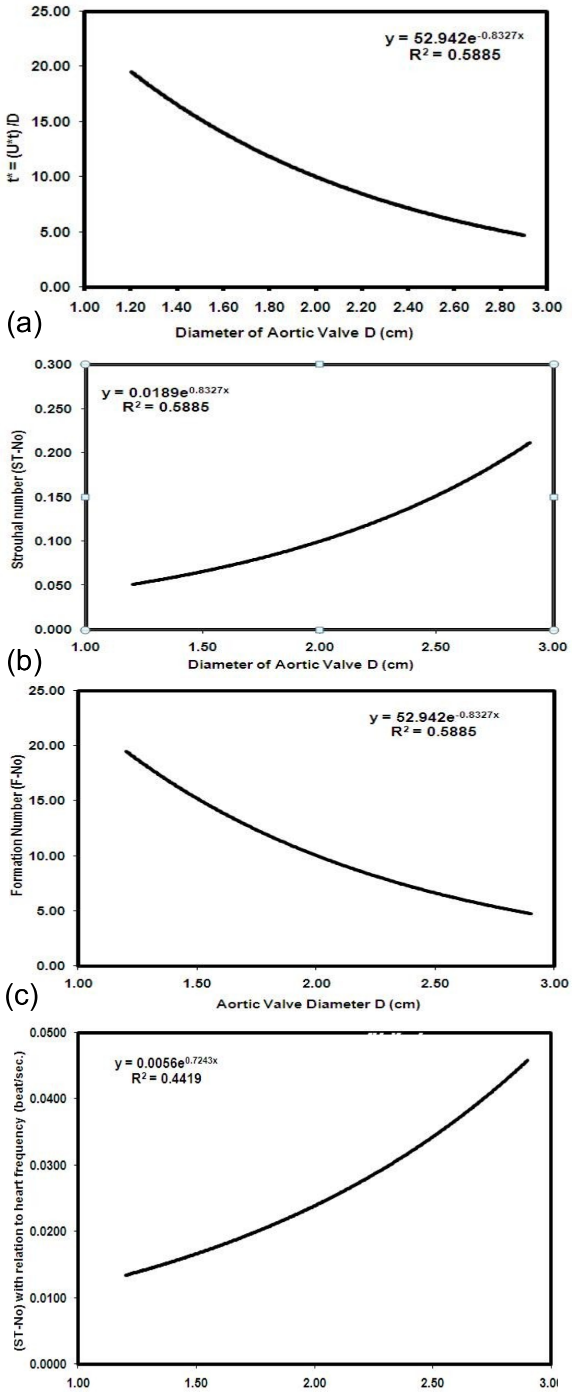

Figure 1: The relation between the Diameter of Aortic Valve D (cm) and. (a) the vortex formation time (t* = (U*t) /D), (b) Strouhal number (ST-No), (c) the formation number (F-No), and (d) the (ST-No) with relation to heart frequency (beat/sec.). for Normal Aortic Valve Subjects.

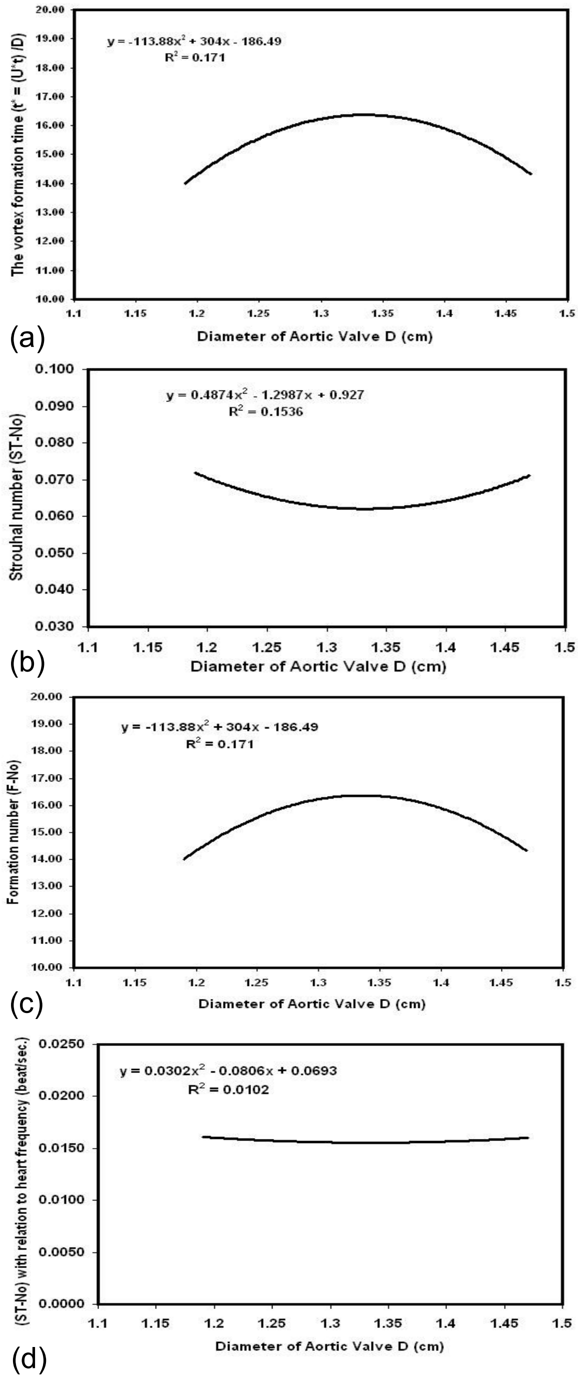

Figure 2: The relation between the Diameter of Aortic Valve D (cm) and. (a) the vortex formation time (t* = (U*t) /D), (b) Strouhal number (ST-No), (c) the formation number (F-No), and (d) the (ST-No) with relation to heart frequency (beat/sec.). For stenotic aortic valve subjects.

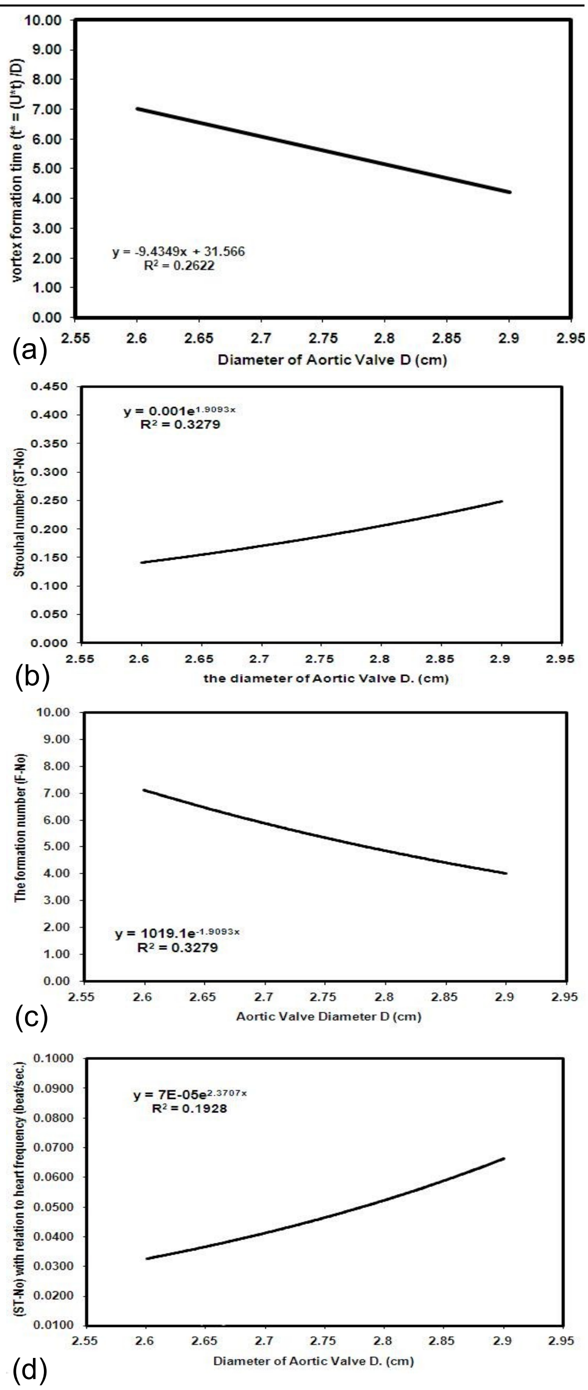

Figure 3: The relation between the Diameter of Aortic Valve D (cm) and. (a) the vortex formation time (t* = (U*t) /D), (b) Strouhal number (ST-No), (c) the formation number (F-No), and (d) the (ST-No) with relation to heart frequency (beat/sec.). for Regurgitate Aortic Valve Subjects.

Discussion

It has been found that the mean values and standard deviation of (ST-No) and (F-No) for normal, stenotic, and for regurgitate aortic valve subjects are shown espectively in Table 1. The results show that (ST-No) of normal aortic valve is larger than that for stenotic, this may indicate that the inertial effects of normal valve are larger than those of stenotic valve, because pressure energy is expanded to overcome inertia rather than converted solely to kinetic energy. The results obtained prove to be significant elevated (ST-No) with aortic valve dimensions, and the improvement in efficiency decreases with increasing Strouhal number. A significant elevated (F-No) has been also noted and the relation is inversely with aortic valve area. The mean ejection time value of subjects with aortic stenosis decreased significantly when compared with normal controls (P<0.005), while it is increased for regurgitate aortic valve group [16]. The Strouhal number is a measure of the ratio of fluid unsteady inertial effects (as measured the frequency parameter) to the fluid convicted inertial effects (as measured by the kinematics mean velocity) [15]. The importance of pulsatile flow conditions has been demonstrated by Gharib[15], who proposed that the non-dimensional Strouhal number is not appropriate for describing the flow through the left ventricle. One of the variables in the Strouhal number is the heart beat frequency (f). There is more than 90% variation in the flow velocities in the left ventricle, because the flow in the left ventricle acts more like a single transient vortex puff than a continuous jet [14]. The normalized velocity field's (x, t), v for each simulation at the beginning of both the ejection and filling phase. In general, increasing the Strouhal number results in smaller but stronger circularly shaped vortices. At the beginning of the ejection phase, the position of the upper and lower ventricular inflow vortices is closer to the valve base [17]. At the beginning of ventricular filling, an increasing Strouhal number generally results in stronger aortic outflow vortices. Furthermore, the lower ventricular inflow vortex and the secondary lower ventricular inflow vortex remains inside the ventricular cavity and increase in size and strength with increasing Strouhal number. Their position is located more toward the aortic opening for decreasing Strouhal number [17].

Table 1: The mean values and standard deviation of (ST-No) and (F-No) for normal aortic valve subjects, stenotic, and for regurgitate aortic valve subjects.

Group	Means ± SD (ST -No)	Means ± SD (F-No)	Probability
Normal	**1.55 ± 0.55**	**10.12 ± 3.16**	**<0.005**
Stenotic	**0.939± 0.14**	**I5.82± 2.20**	**<0.005**
Regurgitate	**2.823±0.99**	**5.722± 1.68**	**<0.005**
Confidence interval of the mean			**0.822-1.724**
T –test			**Significantly**
Probability			**< 0.005**

Conclusion

1- Determination of the Strouhal number and formation number is useful for studying the interaction between the mitral and aortic valves of the heart. It is concluded that the regurgitate volume that is necessary to close the valve, depends on the stroke volume and the frequency of the flow' pulses applied. The left ventricle, the aortic, and mitral valve are located side by side; an interdependence of the dynamic behavior of the valves is expected. 2- The study of vortex formation process provides good information about the factors that affect the ejection blood flow through aortic valve to human body and a lout using the ultrasound waves to determine the importance of the physical factors and the changes that will happen in the shape of the aortic valve. 3- The study of these physical factors is important in determining the values of the Strouhal Number and determining the suitability of the artificial valves and their efficiency. Results show that the regurgitate volumes changes for variations in the flow conditions,

4. The study of the formation number and Strouhal number' is very important to determine the severity of the stenotic and regurgitate aortic valve and gives a good parameters that can be used in medical diagnosis.

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