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Original Research Article

A new approach in studying left ventricular diastole and systole

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Abstract

This study proposes a new vision in characterizing the ventricular diastole and systole. The approach is made starting from energetic consideration, by applying the energy conservation low for the blood entering from left atrium in to left ventricle during diastole period. We had proposed two brand new coefficients to describe the cardiac cycle and we had verified if the coefficients are correlated with classically used parameters. We consider that the energetic approach take into consideration the whole mechanical movement that is happening inside the heart and can offer a very synthetic and scientific solid view about the cardiac cycle. The new coefficients are simply to be calculated and as you will see from our research the correlation with other classically used parameters is obvious.

Keywords: Ecocardiography, Elasticity coefficient, Mechanical impedance, Myocardium elasticity, Left ventricular diastole, Blood speed waves

INTRODUCTION

In the following research we had studied the blood flow during ventricular diastole and ventricular systole. We had defined two new coefficients that help in understanding heart functioning and in diagnostic decision.

The fluids, by applying an external force, do not reach an equilibrium deformation, the degree of deformation changes continuously over time, and the deformation is not recovered after the removal of the external force. This phenomenon is called flow.

Prandtl (van de Vosse and van Dongen, 1998) attempted to overcome the shortcomings of the invisible fluid model theories and introduced the concept of hydrodynamic boundary.

According to this theory at the interface between a fluid and a solid boundary there is formed an area in which the interactions between fluid and solid manifest as resistance forces opposing the flow. Flow Outside of the boundary layer is devoid of internal resistances, and therefore the motion equations of ideal fluids remain valid.

Real fluids are those that resist to flow due to frictional forces between layers. The intensity of these forces is expressed by the dynamic viscosity of the fluid. Real fluids are therefore viscous.

This flow resistance is also called the mechanical impedance of the fluids

$Z=dF/dv$

For many fluids, the viscosity depends only on the state parameters (temperature and pressure) and does not depend on the stresses to which the fluid is subjected (deformation forces and deformation velocity) (Erina and Sándor, 2013).
These fluids are called viscous or Newtonian fluids. We will further consider that blood is such a Newtonian fluid.

MATERIAL AND METHOD

Mechanical impedance at the aortic ring, Za

From a physical point of view, we have seen that a Z size called mechanical impedance can be defined which characterizes "the strength with which a fluid has to be

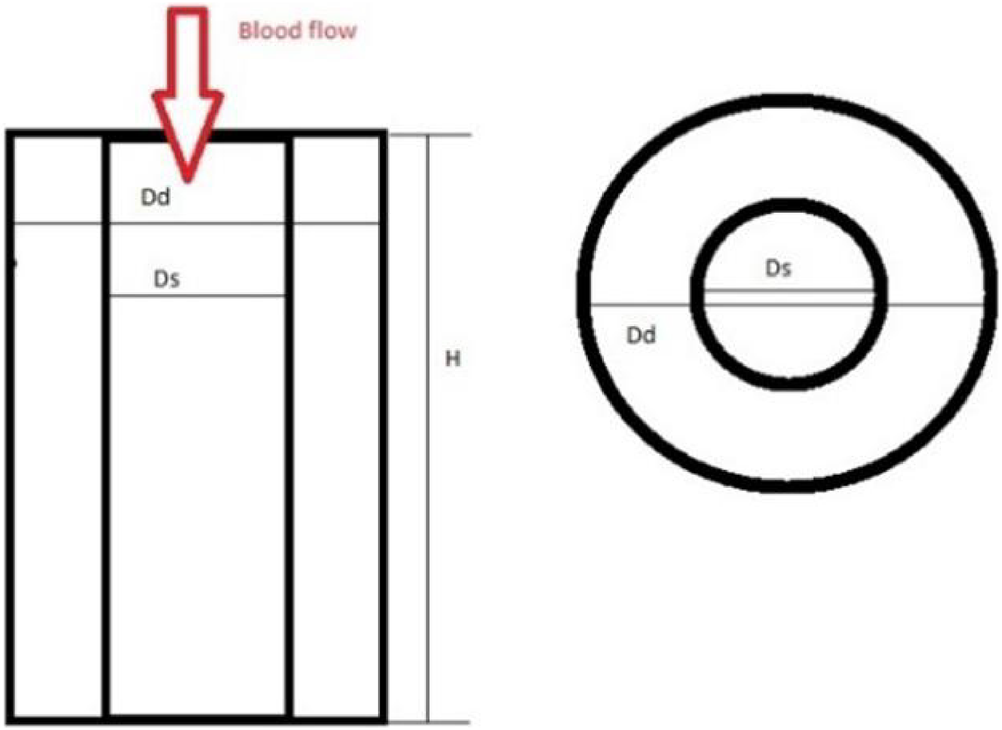

Figure 1. The schematic filling of LV; *D*d – diastolic diameter of LV; *D*s – systolic diameter of LV; *H* length of LV.

pushed through an orifice for it to reach a certain speed." We will basically see what the contraction force required to produce the appropriate blood flow is part of the following formula.

Z=dF/dv

If we consider the force developed by left ventricular contraction in order to produce the blod flow through the aortic valve than we will have a mathematical form for Za (Erina and Sándor, 2013).
The impedance at the aortic ring named, Za is as follow:

$Za = p_a \times S_a / v_a$

p_a – pressure at the aortic rind in the systole time
S_a – aorta transversal restion $Sa = \pi R_a^2$, R_a – radius of aortic ring
v_a – blood speed when entering the aorta

Elasticity coefficient of miocardium, k

In our study, we had made the following assumption as working hypothesis using basic concepts in theoretical description of heart functioning (Nagueh et al., 2009; van de Vosse and van Dongen, 1998): (1) the shape of the left ventricle (LV) is a cylinder, and (2) during contraction of LV the transversal deformation (strain) is much bigger than the longitudinal deformation (strain).

Elastic energy stored in the myocardium is:

$$E_{pe} = k\frac{\Delta x^2}{2} \quad (1)$$

where: E_{pe} – elastic energy, *k* – myocardium elasticity coefficient, *x* – transversal deformation (strain) of LV. x is the variation of the length of the transversal muscle fibber.
The kinetic energy of blood at the entrance through the mitral valve during E wave is:

$$E_c = m\frac{v^2}{2} = \rho V\frac{v^2}{2} \quad (2)$$

where: E_c – kinetic energy, *M* – mass of blood, ρ – blood density, *V* – blood volume, *v* – blood speed through the mitral valve during E wave.
In Figure 1 (new-approach Figure 1) we have the schematic filling of LV; *D*d – diastolic diameter of LV; *D*s – systolic diameter of LV; *H* length of LV).
Applying normal geometry, we can calculate (using parameters defined in the legend of Figure 1)
- the blood volume entering to the LV (Eq. 3),

$$V = \frac{\pi H}{4}\left(Dd^2 - Ds^2\right) \quad (3)$$

- the transversal deformation Δ*x* (The transversal deformation represents the variation of the muscular fibre length. We had considered that the muscular fibre is

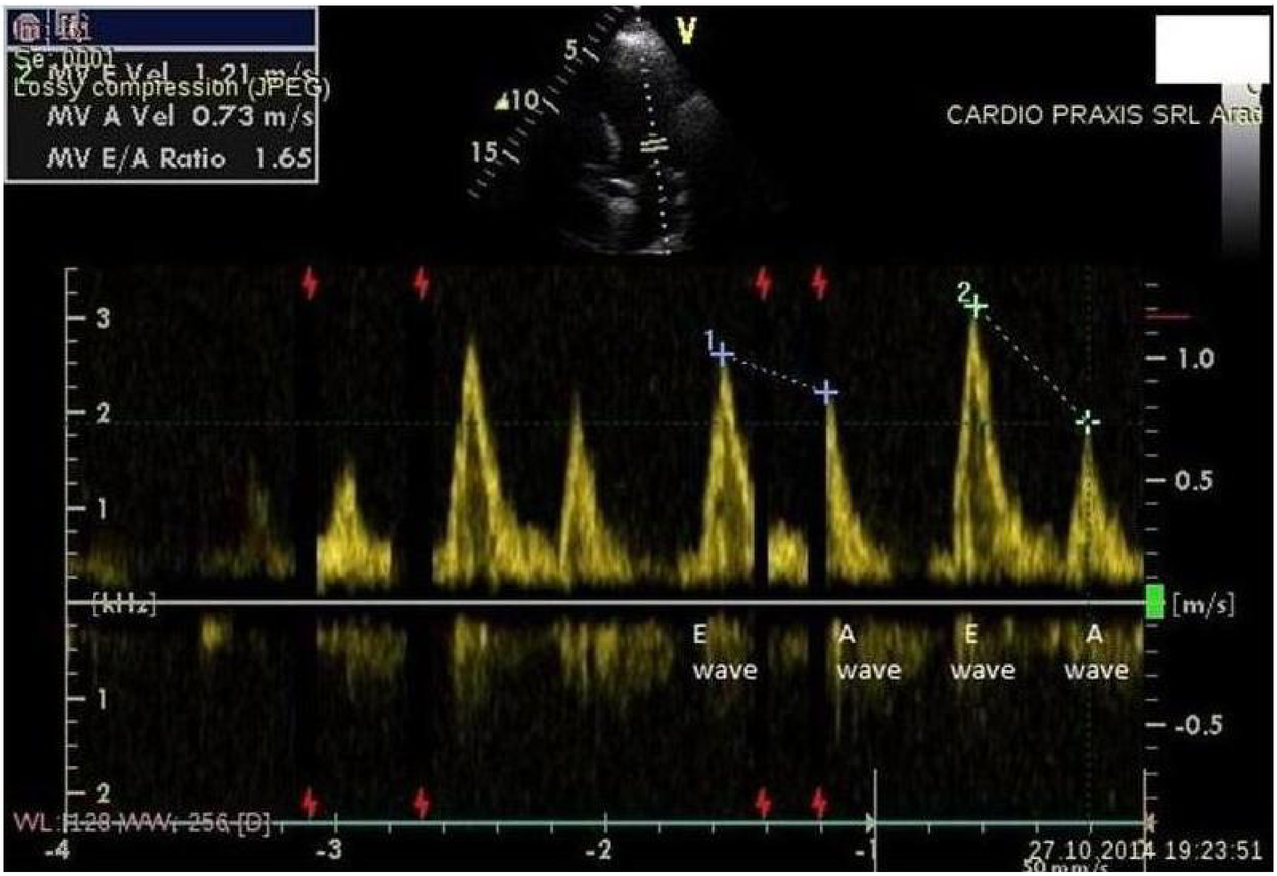

Figure 2. The ecoghraphyc image of Waves E and A (blood speed waves entering in LV)

transversal so the variation if his length is the difference of the length of the circle in diastolic phase versus the systolic phase.) (Eq. 4),

$$\Delta x = \pi\left(Dd - Ds\right) \tag{4}$$

- the ejection fraction (*EF*) (Eq. 5).

$$EF = 1 - \left(\frac{Ds}{Dd}\right)^2 \tag{5}$$

By applying the energy conservation law as equation (1) = equation (2) and using equations (3), (4), and (5) we get as follows:

$$E_{pe} = E_c, k\frac{\Delta x^2}{2} = \rho V\frac{v^2}{2} \Rightarrow k = \frac{\rho\pi H}{4}\frac{\left(Dd^2 - Ds^2\right)v^2}{\pi^2\left(Dd - Ds\right)^2}$$

(6)

resulting in:

$$k = \frac{\rho H}{4\pi}\left(1 - 2\sqrt{1 - EF}\right)v^2 \tag{7}$$

That is the formula we will use for calculating *k* in analysing recorded data on patients.

Correlation study between elasticity coefficient and blood speed and volume ratio between e wave and a wave

Let's analyze the eco image of Waves E and A (new-approach Figure 2). In the figure you can see an echocardiographic image where E and A waves are observed. Also in the upper left corner of the figure we can see the E / A ratio = 1.65, a good ratio. It is also noticed that the wave area E between the wave line and the horizontal axis is greater than the wave area A. The E and A wave areas, respectively, are proportional to the volume of blood absorbed in VS during E wave and A wave respectively. So the volume of blood entering VS during E wave is almost double that the one entered during A wave. This is a normal heart functioning (Catherine, 2009).

We had obtained the data with a General Electric Vivid 7 dimensions echocardiograph and we had analyzed by calculating the areas corresponding to E wave and A wave. This ratio is exactly the ratio between the volume of blood entering the left ventricle during fast pre-filling (E wave), and the volume of blood entering the ventricle during atrial contraction (A wave) (Catherine, 2009). To begin with, we will get independent subjects to analyze the E / A blood flow ratio and E / A area blood volume

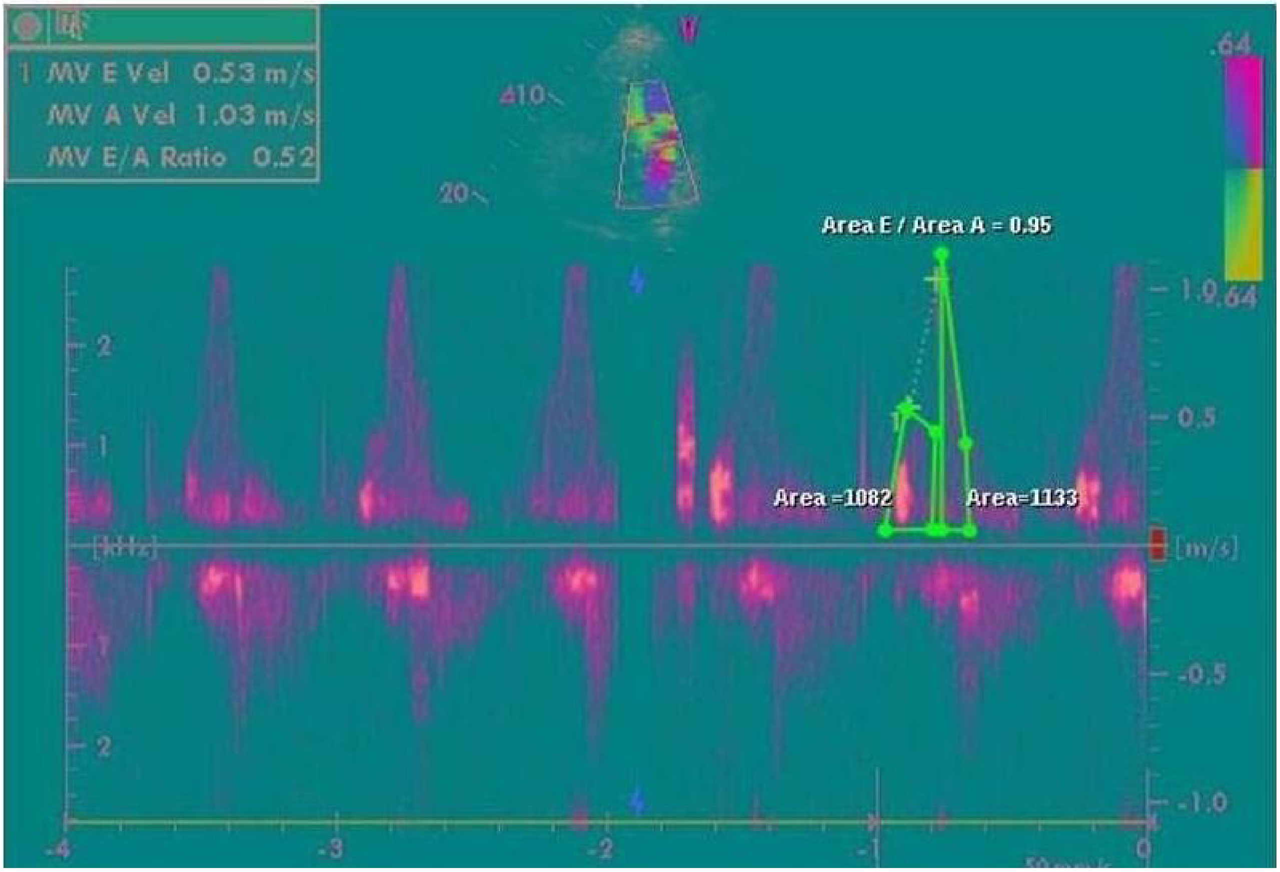

Figure 3. The ecoghraphyc image of Waves E and A – patient AZ (blood speed waves entering in LV)

ratio. In each of these cases we will calculate the elasticity coefficient k and we will comment on the results obtained.

RESULTS

For each subject, we have the image from the echocardiograph with the E and A wave velocity determinations. On this image, using an editing program, we had drowned the wave E and A area and we had calculated these values. We have different situations on each subject.

For AZ. Patient, data taken on 27/10/2014, we have the eco image as in Figure 3 (new-approach Figure 3.)
From this figure we can have:

E/A = 0,52 ; Area E/ Area A = 0,95

It is noted that although the blood velocity during wave E is half than the velocity during the wave A, the volumes of blood from the two filling steps are almost equal. Here we have a classical case of diastolic dysfunction. Ventricular filling is achieved almost 50% during atrial contraction versus 35-40% in the normal case.

Physically we can think of a lack of elasticity of the myocardium. When the heart muscle relaxes during the fast filling (E wave), the more elastic the myocardium is, more volume of blood is entering the ventricle during this period. The normal value of 65-70% is corresponding to an elastic myocardium. If we calculate K, the coefficient of elasticity in this case we get the value K = 21.69 obviously lower than a mean age and gender of 38.5.

This confirms the choice of elasticity coefficient K for myocardium characterization.

For HI patient, data taken on 11/10/2014, we have the eco image as in Figure 4 (new-approach Figure 4)
From this figure we can have:

E/A = 0,80 ; Area E/ Area A = 1,46

From image 4 we can see that although the blood velocity during wave E is 80% from the blood speed in A wave, the volume of blood entering the left ventricle during the fast-filling step is nearly 50% higher than the blood volume in A wave. Here the ventricular complete filling is achieved 60% during E wave and 40% during atrial contraction (a normal case). However, the speed ratio E / A is small. Here we are dealing with a diastolic dysfunction.

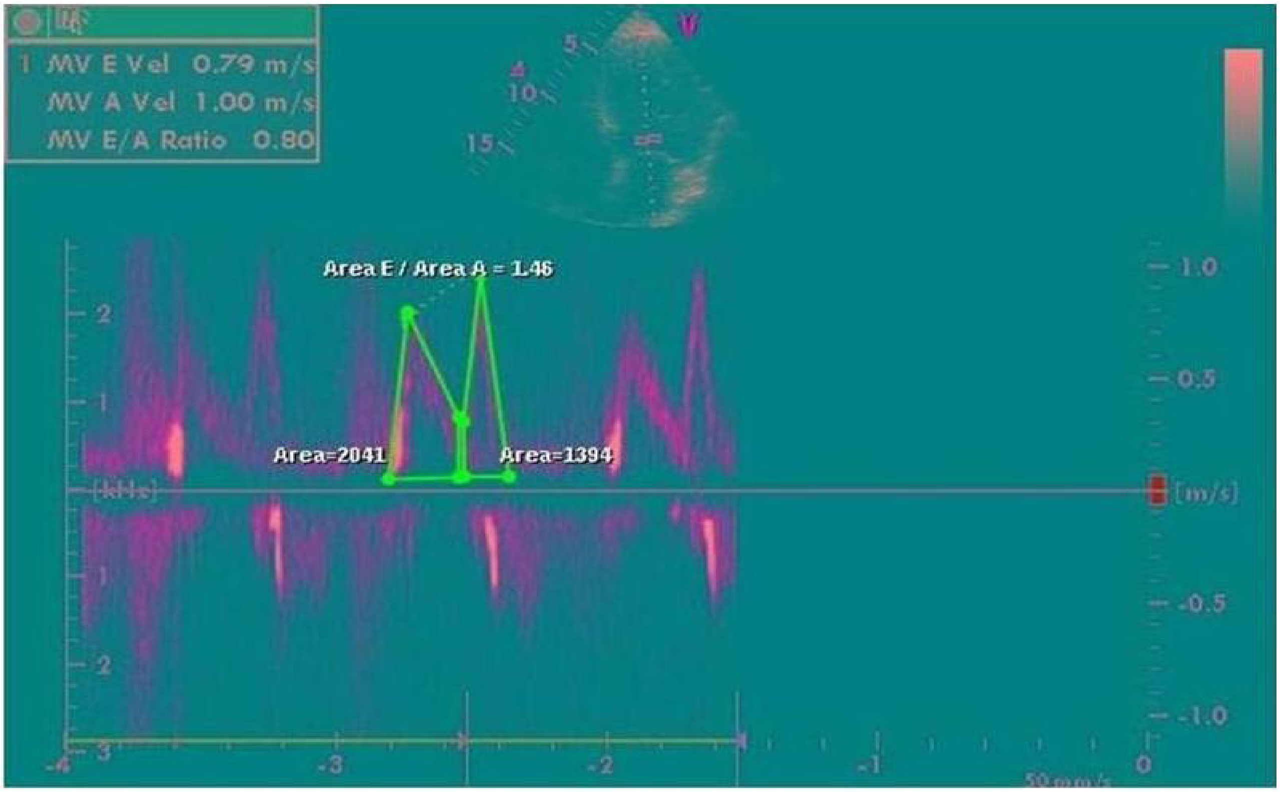

Figure 4. The ecoghraphyc image of Waves E and A – patient HI (blood speed waves entering in LV)

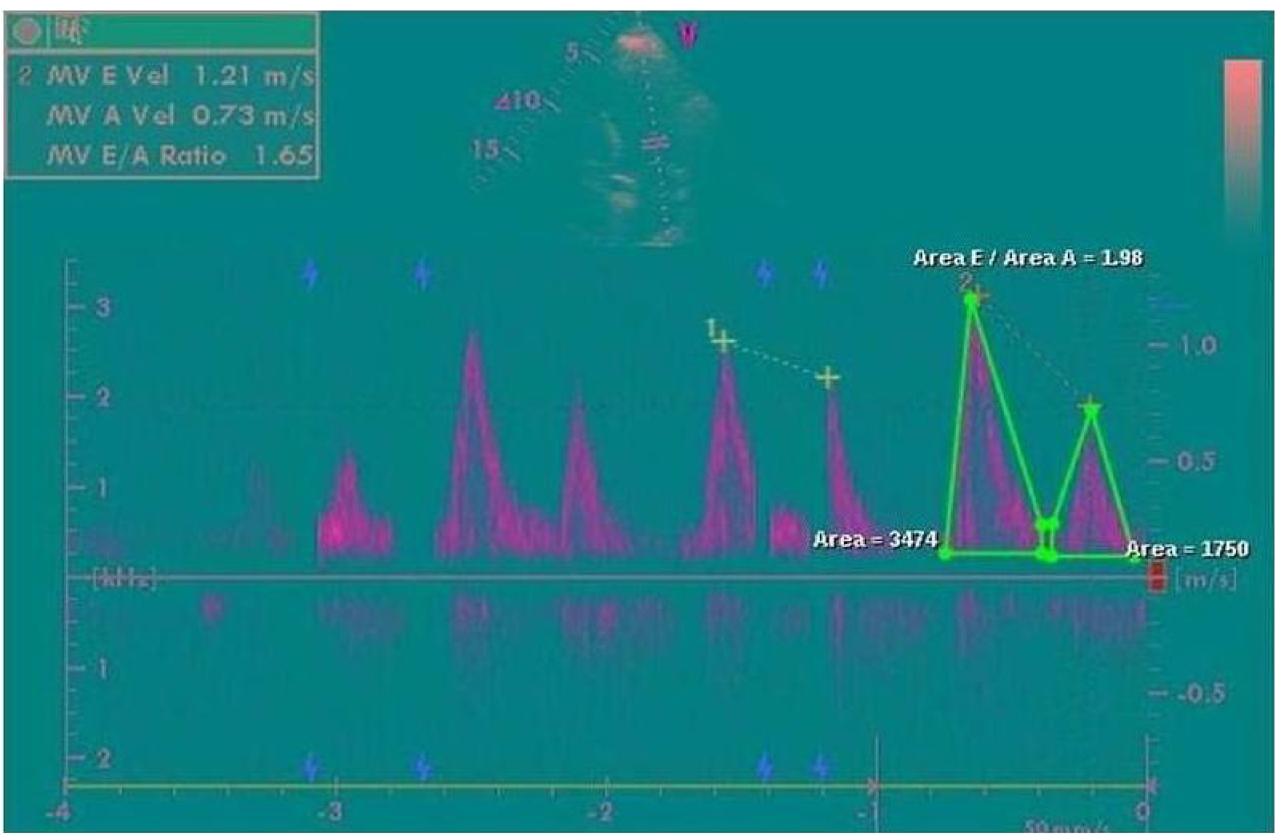

Figure 5. The ecoghraphyc image of Waves E and A – patient MF (blood speed waves entering in LV)

Physically, we can accuse a lack of elasticity of the myocardium because ventricular filling of 60% that occurs during E wave, is due to a long E wave and not to a high velocity in E wave.

If we calculate K, the coefficient of elasticity in this case we get the value K = 16.92 which is much smaller than the average value of 38.5. The heart muscle relaxes hard, is not elastic. It fails to make a good depression for a quick pre-filling.

This confirms the choice of elasticity coefficient K for myocardial characterization.

MF patient, data taken on 27.10.2014 are presented in figure 5 (new-approach Figure 5)

From this figure we can have:

E/A = 1,65 ; Area E/ Area A = 1,98

It is noted that both blood velocity and blood volume during E wave are significantly higher than during A wave. The ventricular filling is achieved 66.5% during E wave and 33.5% during atrial contraction (a normal ventricular filling case). This is a patient case with a normal eco image.

If we calculate K, the coefficient of elasticity in this case we obtain the value K = 46 obviously higher than the average value corresponding to the age and sex of 38.5

This value denotes a healthy and elastic myocardium, a 'trained heart'. We are not in possession of additional subject data to confirm regular exercise.

This confirms the choice of elasticity coefficient K for myocardial characterization.

DISCUSSIONS

The following study denotes that:

- Coefficient of elasticity can characterize the health of myocardium.
- The coefficient of elasticity may indicate cases of diastolic dysfunction at least to the same extent as the E / A ratio. We have seen that in cases of diastolic dysfunction when it is assumed that the myocardium is less elastic, the k coefficient is less than the mean value corresponding to age and sex.
- Correlation between K and E / A gives us the premise of a deeper study of this magnitude.

Analysis of mechanical impedance at aortic level and elasticity coefficient for several cardiac diseases

In this study we will analyze the variations of the three previously defined elements, the aortic impedance Za, the E / A ratio and the coefficient of elasticity k in the case of different cardiac diseases. For four type of heart disease we had calculated an average on decades of the three coefficients. We have seen a close correlation between the causes of cardiac disease and variations in these coefficients.

We started from the Doppler ultrasound database we had used in previous study and we had sorted the patients according to their primary affections. Than we chose several diseases better represented in existing data and we had calculated the averages by decades of the three coefficients.

These heart diseases for what we had study the coefficients are:

Diastolic dysfunction

The abnormality of the filling function or diastolic heart failure is caused by a primary diminution of ventricular distention, in which the VS's ability to accept blood is altered. The ventricle does not fill properly and does not eject enough blood in to aorta. VS ejection fraction under 40% (Catherine, 2009).

Systolic dysfunction

Heart pump function abnormality is known as systolic heart failure, where a decrease in myocardium contractility results in a myocardium dilation. Decreasing the left ventricular (LV) contractility tends to reduce LV ejection volume, increasing the blood volume that remain not pumped and forcing the ventricle to dilatate to maintain the volume constantly (the Franck-Starling phenomenon) (Catherine, 2009). This dilation accompanies a reduction in diastolic distention, resulting an increase in pressure upstream of the ventricle. It is also called Cardiac Insufficiency with low ejection fraction (EF <35-40%). It may or may not have valvular disorders.

LVH (Left Ventricular Hypertrophy)

Concentric cardiac hypertrophy involves thickening of the myocardium resulting in diminishing the size of the left ventricle and right ventricle. It is often associated with death and can contribute to heart failure. In most cases an excessive enlargement of the heart muscle is recorded in the left and right ventricles. These areas are responsible for pumping blood: the left ventricle pumps most of the blood in the body, while the right ventricle supplies blood to the lungs only. Heart hypertrophy may occur in each of the two ventricles (Catherine, 2009). The main problem in LVH is the reduction of blood flow from and to the heart.

Aortic insufficiency

The aortic valve is located in the left ventricle (LV), betw-

Table 1. Mean values of Za, E / A and K for various cardiac diseases

Diagnostic	Za	E/A	K
Diastolic dysfunction Result	0.26	1.00	33.99
Systolic dysfunction Result	0.47	1.26	40.23
LVH Result	0.29	1.04	40.06
Aortic insuf. Result	0.21	0.99	34.97
Mitral insuf. Result	0.28	1.03	38.34
Normal Result	**0.26**	**1.04**	**46.63**

een LV and the root of the aorta. It has three cages inserted at the base of the aorta, in the Valsalva sinuses, where the coronary arteries begin (left and right). They are named depending on the origin of the coronary arteries (Catherine, 2009);
left coronary cusp (corresponds to the Valsalva sinus where the left coronary artery originates);
right coronal cusp (corresponds to the sinus where the right coronary originates)
non-coronary cusp (corresponds to the Valsalva sinus in which there are no coronary arteries).

The aortic valve allows the oxygenated blood from the LV (in the systole) to go through the aorta in all the human body.

Incomplete aortic valve closure and blood return (in diastole) from the aorta in the LV, it is called aortic insufficiency or regurgitation.

Mitral insufficiency

The mitral valve is located between the left ventricle (LV) and the left atrium (LA) and allows the blood to pass through the diastole (when the heart muscle relaxes) in one direction, from the LA to the LV (Catherine, 2009).

Abnormal blood flow from LV to LA in systole (when the heart muscle contracts and the valve is normally closed) it is called mitral failure or mitral regurgitation.

For these types of diseases we calculated the mean values of the three studied parameters (Za, E / A, k) and we obtained the following results.

Results

For each type of disease, in Table 1 (new-approach Table 1), we had calculated the impedance Za, the E / A ratio and the coefficient of elasticity k and their average values.
In the Table I (new-approach Table 1) we have the columns with the following meanings:
Diagnosis = Diagnosis established by the cardiologist who performed the cardio-ecological exam
Za = aortic mechanical impedance
E / A = ratio of blood velocities through the mitral valve during wave E and Wave A
K = coefficient of elasticity of the myocardium
The values obtained for the three coefficients were compared with those obtained for patients with no cardiac disease, ie a normal cardiac eco-cardiac image.

Discussions

For each condition, based on the already established data, we will show that the measured parameters vary in the sense of confirming the physiological changes that take place.
For patients with diastolic dysfunction, we obtained:
Za have an almost equal value to normal, so there is practically no influence on the mechanical impedance at entry into the aorta.
E / A have a lower value than normal that correlates with the fact that LV relaxation at the beginning of diastole is partial and defective specific to diastolic dysfunction
K have a lower value than normal that correlates with the fact that the heart muscle has lost its elasticity.
For patients with systolic dysfunction, we obtained:
Za have a higher value than normal that correlates with the fact that the mechanical impedance at the entrance to the aorta has increased.
E / A have a higher value than normal. This correlates with a decrease in blood velocity in A-wave (poor atrial systole)
K have a lower value than normal. This indicates that the heart muscle is less elastic, i.e. bad relaxation or bad contraction.
For patients presenting LVH, we obtained:
Za have a value almost equal to normal, ie mechanical impedance does not change at the entry into the aorta
E / A is almost equal to normal, ie relaxation and contraction of the heart muscle are normal
K have a lower value than normal, ie, the heart muscle has lost its elasticity, which is evident in left ventricular hypertrophy.
For patients with aortic insufficiency we obtained:
Za is less than normal, ie blood enters in the aorta more easily

E / A have a lower value than normal, ie the velocity in wave A is higher than normal.
K have a lower value than normal, i.e., the heart muscle has lost its elasticity
For patients with mitral insufficiency, we obtained:
Za have a value almost equal to normal
E / A have a value almost equal to normal
K have a lower value than normal, ie, the heart muscle has lost its elasticity
It follows from the above that the three studied indicators behave in the case of various conditions in accordance with what physiologically occurs at the level of the left ventricle and left atrium. So we have all the reasons to use the new defined parameters to characterize the different cardiac diseases.

CONCLUSIONS

In general, from the studies presented in this paper, the following conclusions can be drawn:
- the mechanical impedance defined on the basis of physical concepts is a relevant coefficient in the study of cardiac physiology
- the myocardium elasticity coefficient, defined in study 2 and verified in study 3, is a physical coefficient correlated with the E / A ratio.
- The elasticity coefficient is an indicator of the health of the heart muscle.
- Both the coefficient of elasticity and the mechanical impedance, being relatively simple to calculate quantities, can optionally be entered between the quantities calculated directly by the echocardiograph.
- the study of mechanical impedance and elasticity coefficient should be done not only in age groups and sexes, but also in groups of heart diseases.
- the study of groups of diseases shows a correlation between the values of Za, E / A and K and the pathological changes occurring in LV and LA in these conditions.
- a deepening of the behavior of the three coefficients in various cardiac conditions may lead to the establishment of markers that signalize the occurrence or predisposition towards a particular heart disease.

The direct physical approach of blood flowing inside the heart can generate new, beneficial perspectives in diagnosing various heart conditions, or even in understanding how the ventricles and atriums fill during a heart cycle.

We did not want to propose a new mechanical or mathematical model for studying the functioning of the heart but we approached the heart cicle from another point of view. The emphasis on the elasticity of the myocardium and its quantification with the help of k makes it possible to compare the elasticity in different cases of cardiac diseases.

It would be very interesting to study those three coefficients on different types of activities performed by patients such as office work vs. performance sports or the work of a teacher vs. an emergency doctor.

It remains for these studies to be the subject of another future work. I think this is just the beginning of developing a new perspective on the vital organ of man.

ACKNOWLEDGEMENTS

The present work is original by the nature of the approach of physiological and physical concepts. This approach, through the fluid mechanics and the elastic environment mechanics, can create the premises of some in-depth diagnosis methods of heart disease. The present paper is far from exhaustive. It actually opens the horizon towards a new approach to heart physiology.

We did not intend to give an equation describing the movement of blood inside the heart. We have created the premises of studying the functioning of the heart from a band new perspective. Here is the originality of this thesis. The two new coefficients defined here are just the beginning of a series of new elements dedicated to help in the complicated process of early diagnosis of cardiac problems and to enrich the global image we have on the human heart. As a vital organ of first degree, the heart deserves our full attention from all possible perspectives.

The mechanical impedance at the level of the aortic ring is defined for the first time in this paper. The study of its variation and correlations with classically used coefficients in the diagnosis of heart function is a complete original study. We have shown that the mechanical impedance at the level of the aortic ring can be taken into account when studying diastolic dysfunction in particular.

The coefficient of elasticity defined and analyzed in this paper appears here for the first time. It is newly defined here and the analysis made on different cases shows that it can be used as an indicator of myocardium elasticity. Moreover, the myocardium elasticity coefficient offers the possibility to see the myocardium as an elastic environment with all the resulting properties related to the propagation of the elastic waves.

Mechanical impedance at the level of the aortic ring has been used in other international studies[1], but we do not know nothing about the existence of a correlation study between Za and other classical coefficients used in the diagnosis of cardiac disease.

Carrying out a study of the coefficient of elasticity on different groups of work or physical activities could highlight areas and risk factors for cardiac affections.

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