Use of heart blood flow analysis in clinical practice

A. K. Macpherson[1], S. Neti[1], M. Averbach[2], P. A. Macpherson[3] & C. Chutakositkanon[4]
[1]*Institute of Biomedical Engineering and Mathematical Biology, Lehigh University, USA*
[2]*Division of Cardiology, St Luke's Hospital, USA*
[3]*Department of Applied Technology, Rogers State University, USA*
[4]*Department of Mechanical Engineering, Mahidol University, Thailand*

Abstract

Often in the treatment of patients echocardiograms are performed to analyse cardiac function. As part of the calculation the shear and normal stress on the endocardial surface of the left ventricle can be calculated. This was undertaken for five elderly women patients undergoing stress testing. It was found that when the stress was plotted as a function of strain rate the expected variation would be a linear increase in stress. In some patients there was initially a sharp increase in stress with strain rate then an abrupt change in the stress at the apex or at the mitral valve annulus. With further increase in strain rate the rate of increase in stress decreased. This would suggest that there was some defect in the wall structure. The variation of ventricular volume with strain rate can be obtained. In this case the volume should decrease initially and as the strain rate increases the volume change becomes less. In two of the five patients the expected initial rise in stress did not occur. This suggests a lack of strength of the ventricle. As expected these were not the same patients where the abrupt increase in stress occurred. Such information may be helpful to a clinician in reaching a diagnosis.
Keywords: cardiography, blood flow, echocardiograms, patient diagnosis, stress test, dobutamine.

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1 Introduction

Physicians obtain a graphical outline of the heart's movement using high-frequency sound waves, called ultrasound. The result is called an echocardiogram (known as an echo). This test also provides pictures of the heart's valves and chambers. When combined with Doppler ultrasound and colour Doppler, pictures of the blood flow across the heart's valves can be obtained as shown in figure 1.

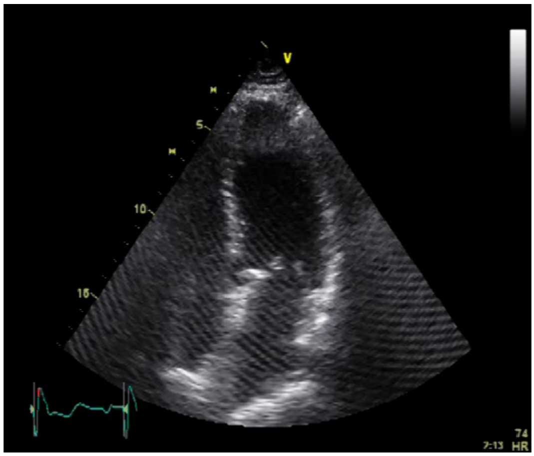

Figure 1: Echocardiogram that could be machine read.

It is possible to undertake the calculation of blood flow to include the whole of the left ventricle using the rate of change of the myocardium and the septum walls [1]. This additional information would be useful for physicians in making a diagnosis of a patient's condition. If the quality of the echo is very good, such as those produced by the equipment manufacturers, then automating the reading of the position of the heart walls can be undertaken. However the quality of many echos is such that it is difficult to discern the edge of the heart, figure 2.

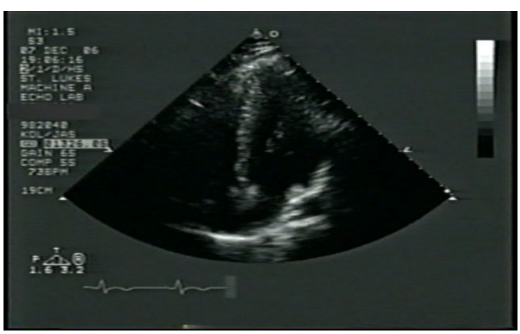

Figure 2: Echocardiogram which could not be machine read.

Thus a problem arises in implementing this on a wide scale as it would be necessary to automate the reading of the position of the heart walls. As the equipment improves in ease of use this should not present a problem.

2 Method of calculation

The general method of calculation used here has been described previously [3, 4]. The method is based on [5] and known as the immersed boundary method. The modification made in the method is that instead of specifying the boundary force the shape of the ventricle as a function of time is taken from the echocardiograms. The immersed boundary method has been reviewed in [6]. In the solution the blood flow into the left atrium is simulated by a source distributed throughout the atrium. In order to conserve mass sinks are distribute around the periphery of the integration domain. The change in shape is obtained from the echocardiograms and used as boundary conditions for the flow. The source strength has to match the change in volume of the ventricle. The valves have to be modelled as thicker than in reality as Lagranian integration must go around both sides of the valve. The Navier-Stokes equations are then solved with a predictor corrector scheme [4].

The Navier Stokes equations defined on an x-y Cartesian co-ordinate system for an incompressible fluid are

$$\rho\left(\frac{\partial \hat{u}}{\partial t} + \hat{u} \bullet \nabla \hat{u}\right) + \nabla p = \mu \nabla^2 \hat{u} + \hat{F} \tag{1}$$

$$\nabla \hat{u} = 0 \tag{2}$$

where $\hat{u}$ is the velocity vector, ρ is the density, t is the time, p is the pressure and the viscosity is μ.

The boundary force $\hat{F}$ arising from the heart muscles is

$$\hat{F}(\hat{x},t) = \int_0^L \hat{f}(s,t)\delta\left(\hat{x} - \hat{X}(s,t)\right)ds \tag{3}$$

Here $\hat{f}$ is the force on the boundary element at the point s defined on a Lagrangian system where $\hat{x}$ is defined on the Cartesian system and $\hat{X}^n$ is the *nth* point on the Lagrangian system

The flow velocities and pressures can be used to calculate the stresses on the surface of the heart walls. These forces can then be used to examine the microscopic interaction with the cells in the heart wall (endocardium).

The first step in the solution involves obtaining the shape of the ventricle at various times. This is often difficult as echocardiogram images are sometimes indistinct. Following a method often used by echocardiographers only five images in a cardiac cycle were selected. One image when the valves were closed, a second image when the valves were fully open, a third just before the atrium starts to contract, one at the end of the ventricle filling (diastole) stage and a

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final one as the aortic valve opens. A linear variation was assumed between each image, time frame. It was assumed that the motion of the wall would be normal to the surface. As described below the times required for valve opening and atrium contraction can be obtained from Doppler measurements of the velocity through the mitral valve and the shape was obtained from the echocardiogram contained many irregularities. The echocardiogram tracing was obtained as a digital image. If the source was allowed to start while the valves were closed then the program would fail due to excessive pressure. Similarly the wall could not be allowed to start moving until the source started. Thus an initial short period was required without source or wall motion to allow the valves to start opening (these events are independent of fluid motion are dependent on cardiac electrical signals).

The second step required the simulation of the atrium. The atrium changes shape during the diastole stage and thus changes the pressure. However the use of a source in place of the correct inflow pattern to the atrium was an artifice which made the actual atrium shape unimportant. The atrium shape was fixed at near hemispherical shape with valves in the closed and early open positions. After some time the atrium contracts for a period before the mitral valve closed... The shape was expanded and contracted as required for the different sized mitral valves. The source strength was increased slowly as the valves opened in accordance with the increase in volume of the ventricle.

Once the calculation of the flow velocities and pressures were completed the stresses at the walls were calculated. This was undertaken following [7] and [8] as the gradient of the velocity near the wall. As the shear stress is continuous at the wall interface this will be equal to the shear force on the ventricle wall. In accordance with the aim of the research, evaluation of wall stresses, the boundary layer had to be modelled properly... Two points were chosen as close to the wall as possible along a line normal to the surface. A finite difference method was used to obtain the derivative of the velocity along this line. Similarly the velocity normal to the wall was calculated along the same line. As only pressure gradients are used in the calculations, an arbitrary constant was added to the pressure to make it relative to atmospheric pressure.

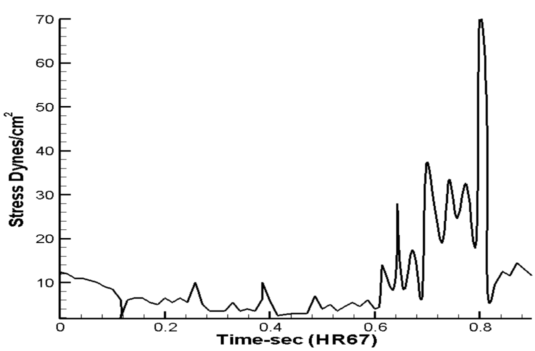

Figure 3: Time variation of shear stress.

3 Results

The results are presented as the variation of time averaged stress with heart rate.

In viewing the results it should be remembered that all five patients were elderly women.

Consider patient 1. From figure 5 it can be seen there is a peak in the shear stress around 90 BPM. This could be due to the apex not relaxing sufficiently as the heart rate increases. This is later, figure 4, reflected in the normal stress around the mitral valve at a higher heart rate. Thus at a later time the mitral valve could develop problems.

Patient 2. Both the shear and normal stresses figures 6 and 7, suggest that this patient appears to be the most normal of the five patients without any sharp changes in stress.

Patient 3. From figures 8 and 9 this patient bears some similarity to patient 1 where there is a peak in the shear stress at the apex and an increase in the normal stress at a slightly higher heart rate. As in patient 1 the peak occurs around 90 BPM. However both the shear and normal stresses increase around the mitral valve with increased heart rate.

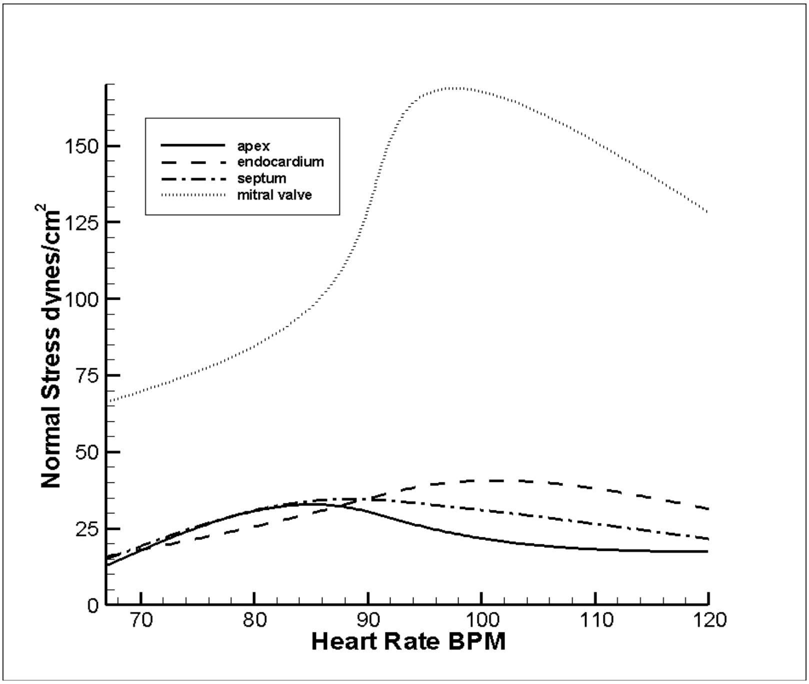

Figure 4: Patient 1 average normal stress over one cycle at various heart rates.

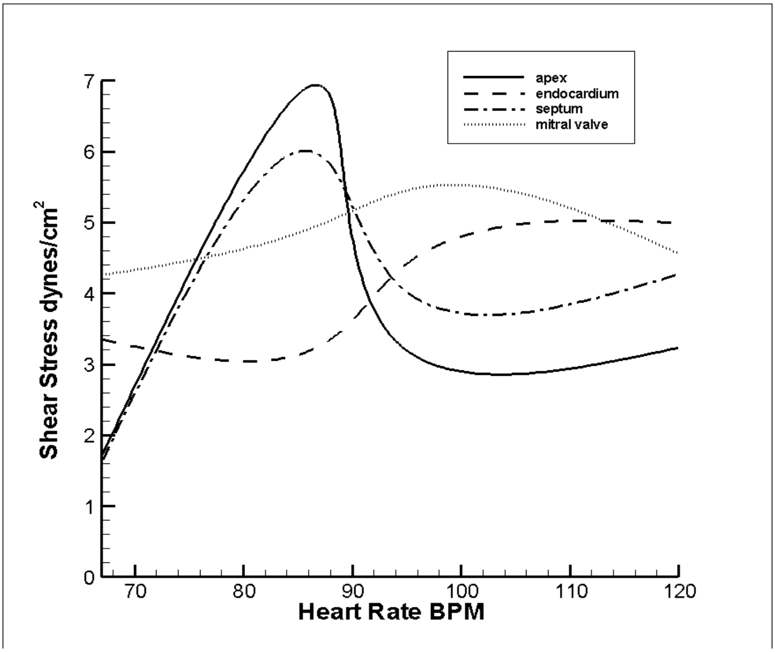

Figure 5: Patient 1 average shear stress over one cycle at various heart rates.

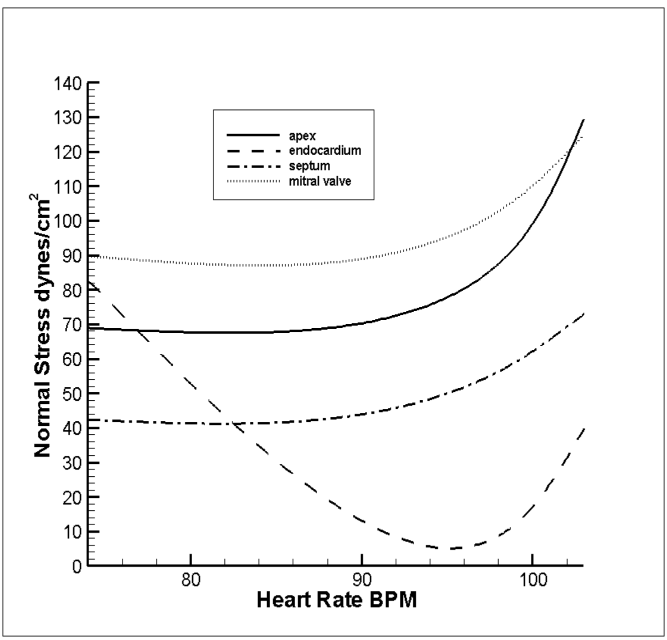

Figure 6: Patient 2 average normal stress over one cycle.

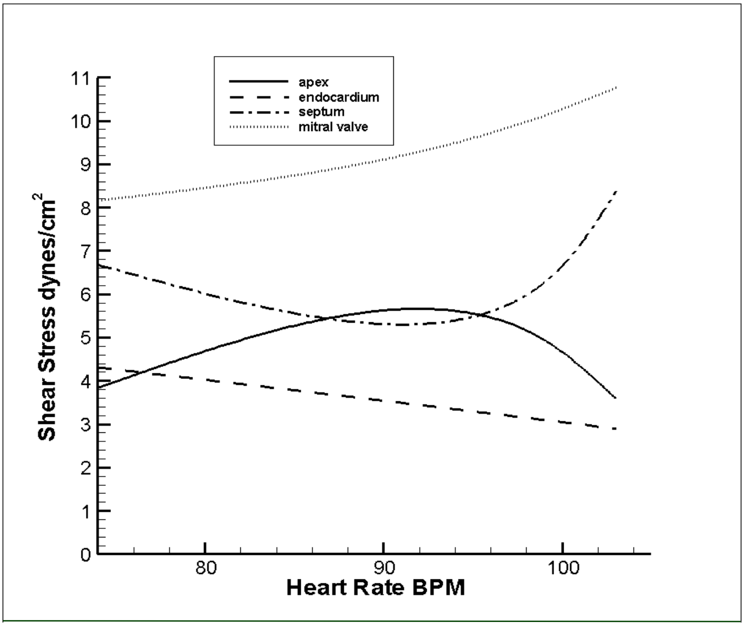

Figure 7: Patient 2 average shear stress over one cycle.

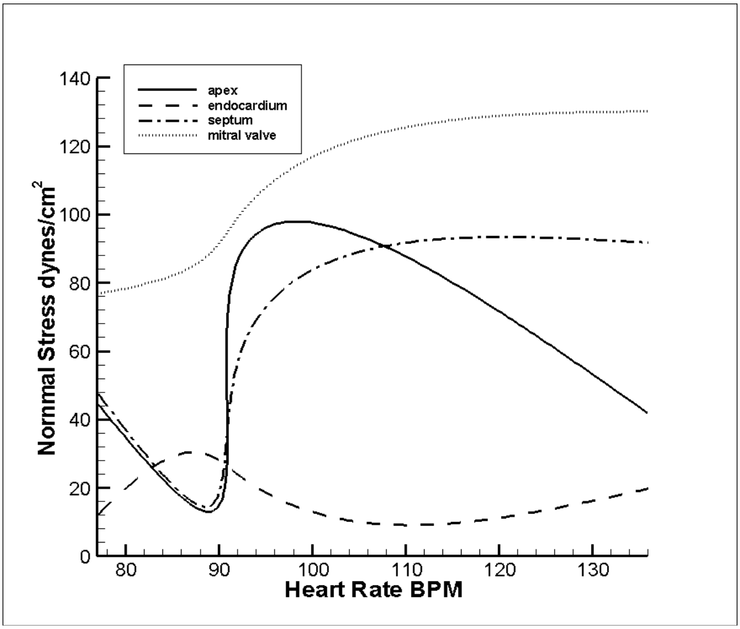

Figure 8: Patient 3 average normal stress over one cycle.

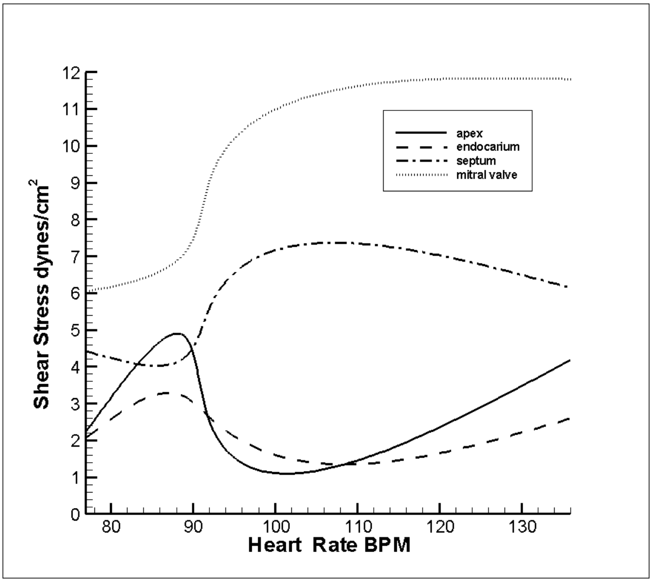

Figure 9: Patient 3 average shear stress over one cycle.

Patient 4. With this patient there is an increase in normal stress around the mitral valve at 95 BPM, figure 11 and a subsequent increase in shear stress figure 10 at the apex occurred at 115 BPM. There are subsequent increases in the shear stress around the mitral valve.

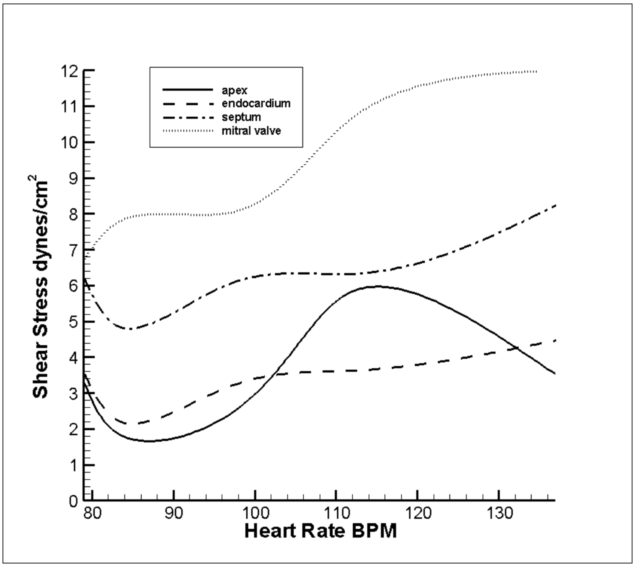

Figure 10: Patient 4 average normal stress over one cycle.

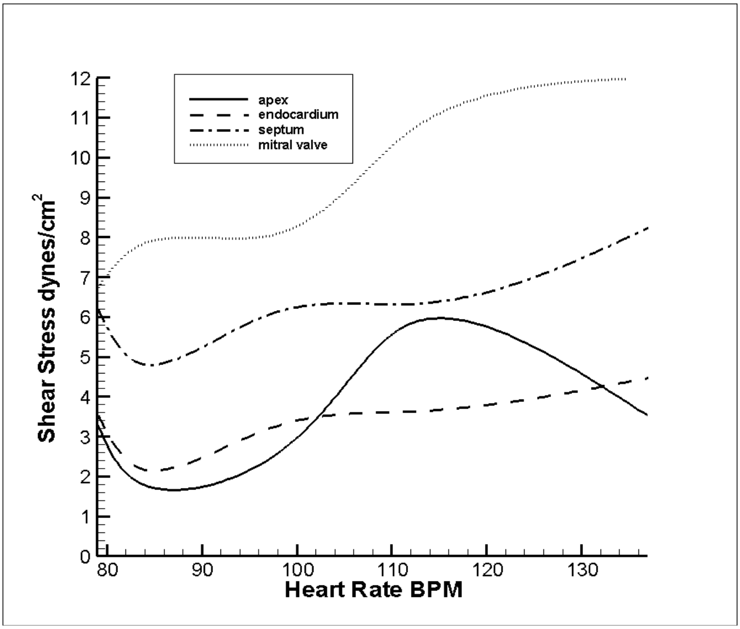

Figure 11: Patient 4 average shear stress over one cycle.

Patient 5. There was a steady increase in stress with BPM figures 12 and 3... Thus it may be possible that this patient would require treatment to lower the stress before such problems as ischemia occurred.

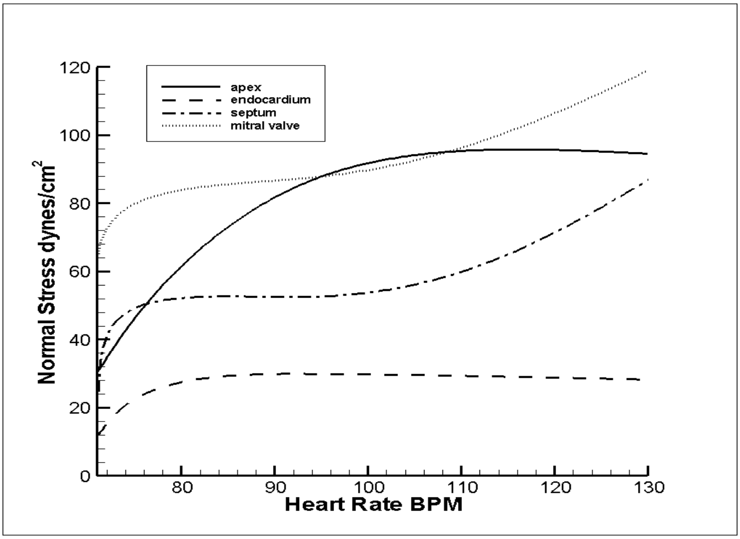

Figure 12: Patient 5 average normal stress over one cycle.

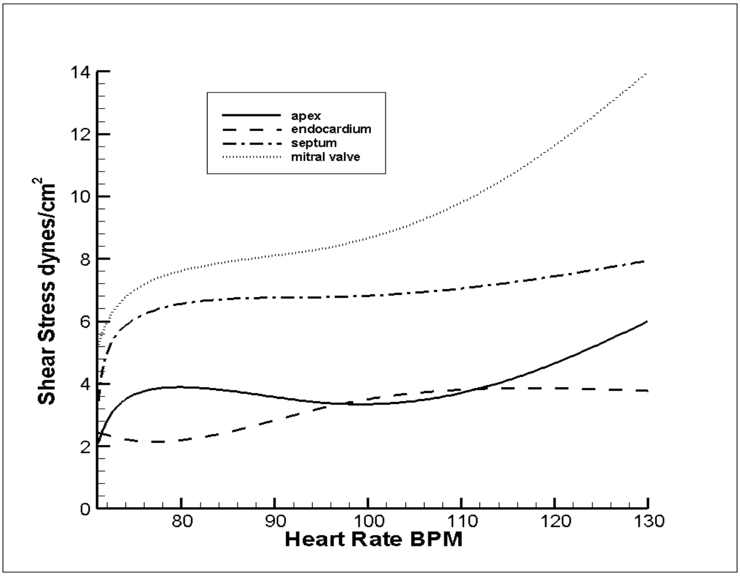

Figure 13: Patient 5 average shear stress over one cycle ventricle with time.

4 Conclusions and future work

It has been demonstrated that additional potentially useful information could be developed from an analysis of the blood flow in the left ventricle. The main problem involved before clinical trials could be undertaken is the automation of the reading of echocardiograms produced in clinician's offices. It would not be possible to recruit busy clinicians for such a study if their intervention was required. This is one of our foremost objectives to use artificial intelligence methods to estimate the ventricle position. It is intended to expand the data base as more data becomes available.

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