

On The Issue of Optimal Trans-mitral Flow

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One of the primary challenges remaining in cardiac hemodynamics is the issue of optimal diastolic filling. The Left Ventricle (LV) fills during the diastolic phase in two separate stages. The first stage starts at the onset mitral valve opening while the second stage begins with the arterial systole. During the first stage, known as E-wave, the trans-mitral flow responds to the rapid pressure drop in LV by accelerating through the valve followed by a decelerating phase due to the weakening of the pressure gradient across the mitral valve. A short pulse of arterial systole generates another pressure gradient and a second flow wave, known as A-wave, in the late diastole. The major filling of the LV (more than %85 of the ejection fraction) occurs during E-wave period.

From various ultrasound and MRI studies, it is now known that the trans-mitral flow during E-wave period results in a rapid roll-up of the flowing blood into vortical structures within the left ventricular body. This vortex formation occurs during the diastolic period. Lee and Talbot [1], tried to apply the concept of the Strouhal number $St = fd/u$, where f is the heart rate, d is the mitral valve diameter, and u is the maximum velocity during diastole, in order to characterize the dynamics of the filling process of the left ventricle. They concluded that the Strouhal number did not indicate any useful trend in characterizing the mitral flow. However, the concept of the Strouhal number has been used successfully by Crow and Champagne [2] to characterize the maximum efficiency of pulsed jets and by Triantafyllou, et al., [3] to characterize the maximum efficiency of swimming fish. In our opinion, to apply a Strouhal frequency approach to the flow in the left ventricle is not appropriate because, in reality, cardiac pulsating filling flow more closely resembles a single transient vortex puff than a continuous jet. This is due to the more than 100% variation in the velocity amplitude during the left ventricle filling process. Therefore, a more appropriate parameter that can demonstrate the dynamics of this vortex roll-up process is a non-dimensional time scale based on the E-wave period. In this report, we refer to this parameter as Formation number which we define as:

$$F = \frac{T\bar{U}}{D}$$

where T is the filling period (E-wave), U is the average velocity for the filling period and D is the mitral valve annulus. This number 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.

To test whether the Formation number could characterize the flow process in the left ventricle, we conducted a series of in vivo tests on 73 normal, healthy subjects ranging in age from 5 years to 84 years. In addition, 8 patients with dilated cardiomyopathy were selected to be examined by the echocardiography described below.

Echocardiography

Two-dimensional, pulsed Doppler echocardiography was performed using commercially available ultrasound machines (Toshiba 140A and Hitachi EUB-165 with 2.5, 3.75, or 5 MHz transducers). We recorded transmittal flows with the ultrasound transducer paced at the cardiac apex and guided by two-dimensional echocardiographic imaging in a four chamber view. A pulsed Doppler sample volume was placed in the center of the atrio-ventricular junction at the level of the mitral annulus. Once adequate transmittal blood flow velocities had been recorded, velocity time integrals for early diastolic transmittal flow (VTI cm) were measured using the track ball systems on the echo systems. The mitral annular diameter (D cm) was also measured at end-diastole using the calibrated track ball measurements from the frozen images. Doppler measurements were averaged over three cardiac beats. Then, the Formation number was calculated as the ratio of DNTI (non- dimensional number).

A power law curve presents the general behavior of the Formation number with age. This curve shows a steady decrease of the Formation number in the early stages until it reaches a base line value of 4.5 for ages over 30. The mean Formation number for the whole data set is about 4.795. A marked decrease in the formation number can be seen for all of the DCM patients ranging from 2.88 to .27 (mean $1.89 \pm .7$).

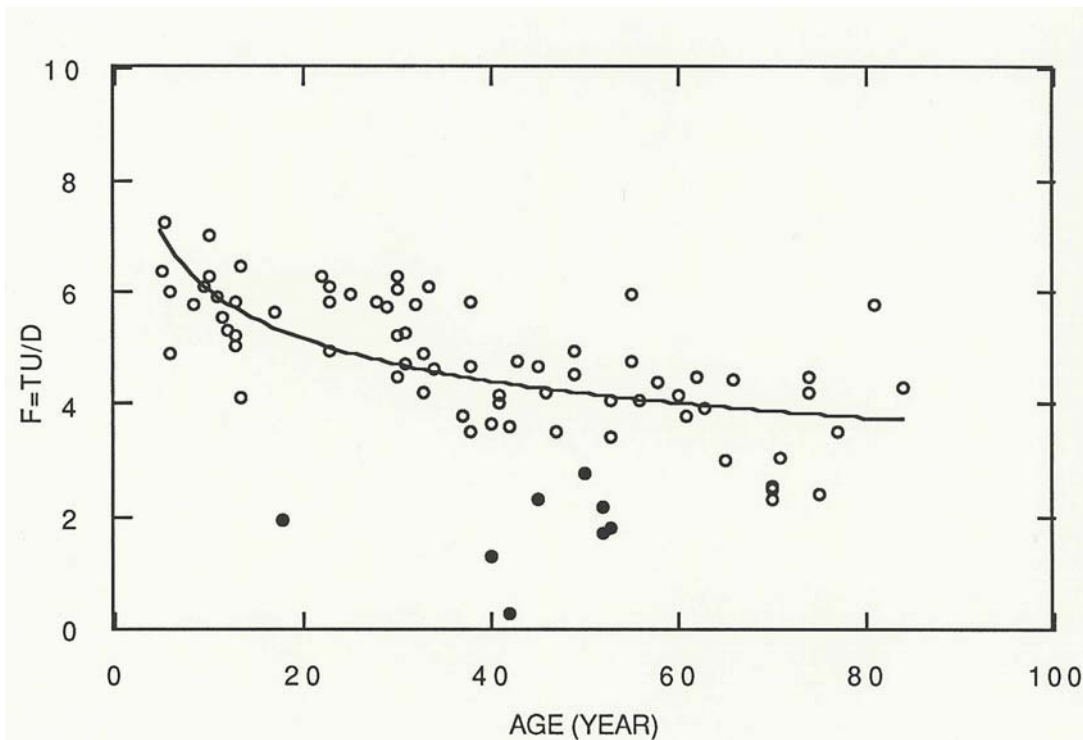


Figure 1. Variation of Formation number with age (o → normal patients, • → DCM)

The mean value of 4 for the formation number appears to indicate the existence of a universal time scale that may describe the optimum range for trans-mitral flow during diastole. The statistical significance and importance of the narrow range of the formation number becomes obvious when one considers the broad spectrum of the ages and backgrounds of the test subjects. A low formation number might indicate poor volume efficiency due to low average velocity or a short diastolic period. A typical example can be found for the cases with dilated cardiomyopathy when decreased systolic function and increased cardiac chamber size is accompanied by reduced left ventricular wall motion, increased filling pressures and abnormal relaxation of heart muscle. A high value of Formation numbers can be indicative of a high heart rate which results in excessive mean velocities through the mitral valve.

The results presented in Figure 1 indicate that the normal heart as a responsive system operates around a Formation number of approximately 4. Whether this base line has a significant fluid mechanical value is an important issue that needed to be addressed through an understanding of the vortex formation process. Gharib et al (1998) showed that the formation number of 4 is directly related to the circulation saturation of forming vortex rings. Kruger and Gharib(2000) extended these studies to show that this range of formation number is associated with the optimal (maximum) impulse that can be produced by a forming vortex ring. These studies all indicate that perhaps the formation number of 4 is an effective parameter for defining

an optimal range of trans-mitral flow dynamics. It is important to mention that other trans-mitral flow parameters such as peak E-wave to A-wave velocity ratio are not as robust as Formation number. In this report, we will discuss these parameters and other important aspects of Formation number in defining the optimal transmitral flow.

References

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