Hemodynamic Evaluation of Rheumatic Valvular Disease with Doppler Echocardiography

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INTRODUCTION

Since the introduction of two-dimensional echocardiography, in the late sixtees (1-3), it has undergone a lot of developments. It is now considered as the time tested, accurate, noninvasive method of demonstrating the cardiac anatomy. However, reliable noninvasive evaluation of cardiovascular hemodynamics was not possible until the introduction of Doppler echocardiography. Earliest application of Doppler was restricted to assess peripheral circulation(4). In recent years it has undergone revolutionary changes. In experienced hand, in adjunct to two-dimensional echocardiography, Doppler study can provide accurate beat to beat information regarding changes in the flow and pressure of the cardiac chambers and the great vessels (5). A detailed description of the theory instrumentation, technique, and applications has been already described (6). This article will review some of the basic principles and clinical applications of Doppler echocardiography in the evaluation of altered hemodynamics in rheumatic valvular heart disease.

BASIC PRINCIPLES

When the source of sound is moving there is change in the frequency of sound. This frequency shift was first described by Doppler in 1842, and is also called Doppler shift. When the beam of ultrasound is reflected off the red blood cells, there occurs a change in the frequency of the emitted sound. The magnitude of change depends on the direction of the flow of blood (RBC). Thus the frequency of the reflected wave will increase if the blood is moving towards the transducer and decreases if it is moving away from it. The Doppler shift (frequency shift), positive or negative is directly proportional to the velocity of the source, i.e., red blood cells. This can be calculated as shown in the equation.

$$F_d = \frac{V \times 2\,Fo\cos\theta}{c}$$

or

$$V = \frac{Fd \times c}{2F_o \times \cos\theta}$$

Where: F_d = frequency shift.
V = Velocity of blood (RBC's) cm/sec
F_o = Frequency of transmitted sound.
C = Speed of sound in the tissue 1560 m/sec
θ = Angle between ultrasound beam and axis of blood flow.

As shown in the equation, except for the angle of beam to the jet of flow (Cos θ), all other factors are constant. If the beam is parallel to the flow (i.e., angle is zero then Cos θ = 1.), the estimation of velocity is accurate. The error introduced by the angulation is significant only if the angle is > 20°. The Doppler shifts (frequency shifts) are processed electronically and the velocity (cm/sec) of the blood flow is displayed (in real time) along the vertical axis. Flow towards the transducer is shown above the zero line, and flow away from the transducer is recorded below the zero line. As the Doppler

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shifts are in the audible range, they are very helpful in obtaining an adequate Doppler study.

Doppler echocardiography has made it possible to calculate the pressure gradient across the stenotic valves and severity of regurgitation across the incompetent valves, which, in the past, required cardiac catheterization. Pressure gradients across the stenotic valve can be calculated using modified Bernoulli equation.

$$P = 4\ V_2^2 - V_1^2$$

Where P = pressure gradient mm Hg across the stenosis

V_1 = Velocity of blood m/sec proximal to stenosis

V_2 = Velocity of blood m/sec distal to the stenosis

As the velocity proximal to stenosis (V_1) is usually $\leqslant$ 1 m/sec, it can be neglected; and therefore, the equation can be simplified

$$P = 4\ V_2^2$$

Pulmonary hypertension is not uncommon in patients with rheumatic heart disease particularly in mitral stenosis. Using a peak systolic velocity of tricuspid regurgitation, right ventricular systolic pressure can be calculated with the help of modified Bernoulli equation

$$RVPs = 4V^2 + RA$$

where RVPs = right ventricular systolic pressure

V = peak velocity of tricuspid regurgitation

RA = Mean right atrial pressure estimated from jugular venous pressure

As the right ventricular outflow is commonly unobstructed in rheumatic heart disease, the systolic pulmonary artery pressure can be estimated. The sensitivity of Doppler to detect tricuspid regurgitation in patients with pulmonary artery hypertension is over 80% (> 50% in those with normal pulmonary artery pressure), (7). Excellent correlation was found between the Doppler estimated pulmonary artery pressure and cardiac catheterization (7,8,9).

Presently two techniques are used, pulsed wave and continuous wave Doppler. Pulsed wave Doppler analyzes the Doppler shifts only in a small area of the heart at one time. Combining the pulsed Doppler with the two-dimensional image, flow and pressure changes can be evaluated by placing the sample volume at a specific region. The main limitation of this technique is that it cannot accurately analyze the flow velocity above a certain range called NyQuist limit, above which, a phenomenon called aliasing occurs.

In this, the signals fold over to the opposite direction, making it difficult to measure the peak velocity.

Continuous wave Doppler can continuously analyze the Doppler shifts of unlimited magnitude. However, as the frequency shifts, all along the beam are analyzed without depth indication, continuous wave Doppler has no range gating. Most machines have both pulsed and continuous wave Doppler techniques.

CLINICAL APPLICATIONS OF DOPPLER

Few points need to be stressed to make the Doppler examination more rewarding.

1. In addition to the sound history and physical examination, complete two-dimensional examination is often helpful.

2. An adequate Doppler signal is the one which has a well defined, clean, envelope and has maximum velocity, both of which ensure that the beam is parallel to the flow.

3. Two-dimensional image is a useful guide to place the sample volume at the site of lesion, however it doesn't ensure parallel beam to flow relationship. Therefore, one should thoroughly scrutinize the two-dimensional directed region, depending more on the audio visual signals.

4. The reliability of the Doppler derived hemodynamic data is not only dependent upon the experience but also on the determination and patience of the operator, to achieve an adequate study.

MITRAL VALVE EXAMINATION

Apical four chamber view is the best position for recording mitral valve flow signals. In pulsed wave Doppler technique the sample volume should be placed at the mitral valve, and left ventricular inflow as well as the left atrium should be scanned. In patients with mitral stenosis and mitral regurgitation, having high velocity flow, with experience, non-imaging transducer beam can be directed across the mitral valve from the apical position. There are early and late diastolic peaks resembling an "M" shaped pattern of the M-mode. As the flow is towards the transducer, it is displayed above the zero line, nornally E wave is higher than A wave. There is no flow signal, recorded during systole; however, in continuous wave Doppler, some of the left ventricular outflow signal may be recorded. Normal mitral valve flow velocity in adults is 1 (0.8-1.3) m/sec.

MITRAL STENOSIS

If there is obstruction to flow, there is local increase in the velocity of blood flow which is proportionate to the severity of obstruction. In mitral stenosis because of the restricted flow, there is pressure drop across the valve and increased diastolic flow velocity. There are two diagnostic criteria for quantitating the severity of mitral stenosis. 1) *Calculating the pressure gradient.* By applying modified Bernoulli equation, we can calculate the peak and the mean diastolic gradient across the mitral valve, Several studies have shown good crrelation with catheterization derived pressure gradients (10,11,12). However, in conditions with increased flow across the mitral valve, e.g., ventricular septal defect, mitral regurgitation, etc. pressure gradient may be present without mitral stenosis (5). Thus, a Doppler study should always be correlated with the clinical findings and two-dimensional echocardiography. Moreover with pressure half time calculation, (as discussed in the later section) it is possible to differenciate such patients.

2) *Pressure halftime and mitral valve area.* In the normal mitral valve there is no restriction to the flow so that at the onset of diastole, there is rapid fall in the left atrial pressure and the gradient across the mitral valve. In mitral stenosis, due to restricted flow, the rate of fall of the left atrial pressure is delayed so that the diastolic gradient is maintained for a longer period. Pressure halftime is defined as the time in milliseconds required for the diastolic gradient to fall by 50% of its value at the onset of diastole. The pressure halftime can be calculated from the velocity curve by equation. See Figure (1).

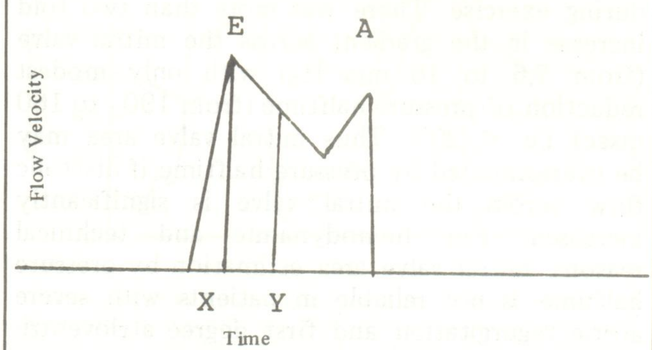

Figure 1

Diagramatic representation of Mitral Valve diastolic flow, illustrating the pressure half time calculation. X is the peak diastolic velocity. If X is divided by $\sqrt{2}$ we get Y. The time interval between X and Y is the time required for the X to decrease by half its value, i.e. pressure half time.

$Vt\ 1/2 = Vp$ where: $Vt\ 1/2$ = velocity at one-half of the initial pressure gradient

Vp=peak diastolic velocity

As discussed above in mitral stenosis, depending on the severity of the lesion, diastolic halftime is increased from normal of 40-60 msec to > 100 msec. Initially studied by Libanoff, et. al. in 1968 (13), cardiac catheterization derived pressure halftimes showed good correlation with the mitral valve area. As pressure halftime is inversely proportional to the severity of mitral stenosis, Hatle, et.al. (14) estimated mitral valve area from the equation:

$$MVA = \frac{220}{\text{pressure half time in msec}}$$

(cm²) where 220 is constant, MVA = mitral valve area

It was proved by them, and later by other study (15) to correlate well with the mitral valve area derived from cardiac catheterization data. Stamm R. B., et.al. (15) studied 30 patients with mitral stenosis. They evaluated the mitral valve area and the mean gradient and fund a close correlation between cardiac catheterization and Doppler with (r=87 and 0.85 respectively).

More interestingly, it has been found that the mitral valve area calculation from pressure halftime can be estimated with reasonable accuracy, even in the presence of altered flow status across the mitral valve (e.g., mitral regurgitation, ventricular septal defect) and arrhythmia (13). However, it has certain limitation. Hatle, et.al. (5) studied 37 patients with mitral stenosis during exercise. There was more than two fold increase in the gradient across the mitral valve (from 7.6 to 16 mm Hg) with only modest reduction of pressure halftime (from 190 - to 160 msec) i.e. < 20%. Thus mitral valve area may be overestimated by pressure halftime if diastolic flow across the mitral valve is significantly increased. For hemodynamic and technical reasons, mitral valve area estimation by pressure halftime is not reliable in patients with severe aortic regurgitation and first degree atrioventricular block.

MITRAL REGURGITATION

For the detection of mitral regurgitation, several studies (16,17) using pulsed wave Doppler technique have shown very high sensitivity and specificity. Commonly, the apical view, with sample volume in the left atrium, just above the mitral valve is useful. Normally, there is no flow signal during systole; however, in patients with mitral regurgitation, there is high velocity (5-6 m/sec) systolic flow below the zero line. Depending upon the severity, these signals may be recorded in the left atrium at variable distance above the mitral valve. As the velocity of signal is very high, aliasing in pulsed wave Doppler interferes to obtain useful information. Fortunately, in most of the patients with rheumatic mitral regurgitation, the jet is along the long axis view, i.e., symmetric; therefore, with the help of audiovisual signals, continuous wave Doppler can easily detect rheumatic mitral regurgitation. Doppler detection of rheumatic mitral regurgitation in many studies (18,19) have shown almost 100% sensitivity and specificity. The sensitivity of Doppler in detection of mitral regurgitation as proved by Paul. A, et. al. for aortic-regurgitation (34) probably exceeds all other noninvasive methods including auscultation.

QUANTITATION OF MITRAL REGURGITATION

Several semiquantitative methods have been described to assess the severity of mitral regurgitation e.g.:

1. Spatial mapping.
2. Strength of the Doppler signal.
3. Left ventricular inflow and outflow velocity.
4. Others.

The most commonly used method is the pulsed Doppler mapping of the regurgitant jet in the left atrium, (19). The severity of mitral regurgitation is graded on the basis of extension of the jet into the left atrium. However as the regurgitant jet is three dimensional, it is more rewarding to scrutinize the left atrium in multiple positions. Moreover, the severity of mitral regurgitation may be underestimated, by this method in patients with huge left atrium. In mitral regurgitation, the left ventricular diastolic inflow velocity is increased which is proportionate to the severity of mitral regurgitation (5). In hyperdynamic states like anemia, thyrotoxicoses etc. mitral inflow velocity may be increased without mitral regurgitation. However in these conditions, there is proportionate increase in both, the left ventricular inflow (diastolic) and outflow velocities (systolic). Where as in mitral regurgitation, there is only increased left ventricular inflow velocity. Roxann Rucky, et. al., (31) evaluated 25 patients with mitral regurgitation for Doppler estimated regurgitant fraction. They observed excellent correlation with angiography (r = 0. 91).

It is not unusual to get a very asymmetric regurgitant jet which is difficult to detect and quantitate by conventional Doppler technique. The recent introduction of color flow imaging has greatly improved the sensitivity and specificity of Doppler echocardiography. Flow imaging is extension of the two-dimensional pulsed wave Doppler. It is a multigated (i.e. has multiple sample volumes) computerized color coded Doppler analysis. It displays real time, flow (color coded) superimposed on two-dimensional image.

The flow away from the transducer is depicted blue and towards the transducer red. Color Doppler has great impact on the conventional Doppler as it can display the direction and extension of the regurgitant jet. In this way it improves the detection and quantitation of regurgitation by Doppler echocardiography. In a recent study (33) in 147 patients, color Doppler technique was found to have 100% sensitivity and specificity for detection and had excellent correlation with catheterization for grading the severity of mitral regurgitation.

AORTIC VALVE

The aortic valve can be best visualized from the apical view. Suprasternal and right parasternal view (with extreme right lateral tilting of the patient) are also useful. If recorded from the apex, the flow is away from the transducer and is recorded below the zero line. Normally there are no flow signals during diastole. However, continuous wave Doppler may record some of the left ventricular inflow diastolic velocity signals. Normal aortic valve systolic flow velocity is 1.35 m/sec (1.10 - 1.7 in adult).

AORTIC STENOSIS

Although pulsed wave Doppler is very sensitive in the detection of aortic stenosis; however, it is difficult to quantitate the severity of aortic stenosis because of the problem of aliasing. In experienced hands, continuous wave Doppler has been a very useful technique of grading the severity of aortic stenosis. (20-25). In all these studies, there was a strong correlation between the Doppler and cardiac catheterization derived gradients (with $r > 0.90$). Using modified Bernoulli equation, instantaneous peak gradient can be estimated across the aortic valve. When compared to catheter derived peak to peak gradient, the Doppler seems to overestimate the gradient. This is because the Doppler estimated gradient is an instantaneous peak gradient, where as, catheter calculates the peak to peak gradient Figure (2). Currently, computerized mean gradients can be easily calculated which has an excellent correlation with the catheterization. It is important to note that quantitation of the severity of aortic stenosis, using a gradient is dependent on the flow across the aortic valve.

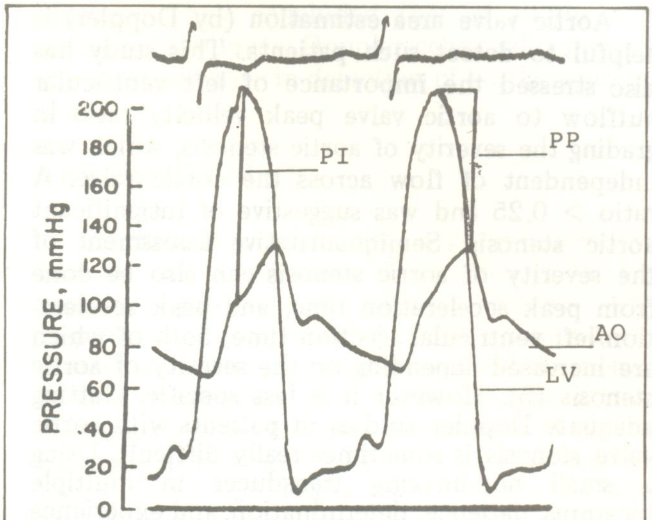

Figure 2.

Aortic (A.O.) and left Ventricular (L.V.) pressure tracing in a patient with Aortic Stenosis. Note that the Doppler estimated gradient peak instantaneous (P.I.) is greater than the catheter measured peak to peak pressure (P.P.)

Thus, false over estimation or under estimation of the severity of aortic stenosis may occur in patients with aortic regurgitation or severe left ventricular dysfunction respectively. In 1984, DC Warth, et. al. (24) described the reliable noninvasive method of estimating the aortic valve area independent of flow across the aortic valve: It showed excellent correlation with catheterization derived aortic valve area (r = 0.99).

Thus using equation of $A_1 = \frac{V_2 \times A_2}{V_1}$ we can calculate the aortic valve area.

WHERE: A_1 = Aortic valve area cm^2.
A_2 = Aortic anulus area cm^2.
V_2 = Mean velocity across the aortic anulus. -m/sec.
V_1 = Mean velocity across the aortic valve m/sec

Using peak velocities instead of mean, have comparable results. A recent prospect study of 100 patients with aortic stenosis by Oh, et. al., (25) from Mayo Clinic has indicated that Doppler echocardiography can reliably estimate the severity of aortic stenosis. In their study, they concluded that the peak systolic velocity across the aortic valve > 4.5 m/sec or Doppler estimated mean gradient > 50 indicated severe aortic stenosis. Patients with a peak velocity < 4.5 m/sec or a mean gradient of < 50 mm Hg may have severe aortic stenosis, particularly in patients with underlying left ventricular dysfunction.

Aortic valve area estimation (by Doppler) is helpful to detect such patients. This study has also stressed the importance of left ventricular outflow to aortic valve peak velocity ratio in grading the severity of aortic stenosis, which was independent of flow across the aortic valve. A ratio > 0.25 and was suggestive of insignificant aortic stenosis. Semiquantitative assessment of the severity of aortic stenosis can also be done from peak acceleration time, and peak acceleration/left ventricular ejection time, both of which are increased depending on the severity of aortic stenosis (5). However it is less specific. Getting adequate Doppler studies in patients with aortic valve stenosis is sometimes really difficult. Using a small non-imaging transducer in multiple locations, patience, determination, and experience are the keys for success.

AORTIC REGURGITATION

Pulsed or continuous wave technique may be used for detection of aortic regurgitation. However, aortic regurgitant flow is high velocity (4-5 m/sec) therefore continuous wave Doppler is preferable. Using apical view high velocity signals are recorded starting with the aortic closure, above the zero line (jet is directed towards the transducer). Although the apical view is the best for evaluation of isolated aortic regurgitation, it may be interfered by the diastolic flow signals of left ventricular inflow. Therefore in patients with associated mitral stenosis or mitral prosthetic valve, the parasternal view is preferred.

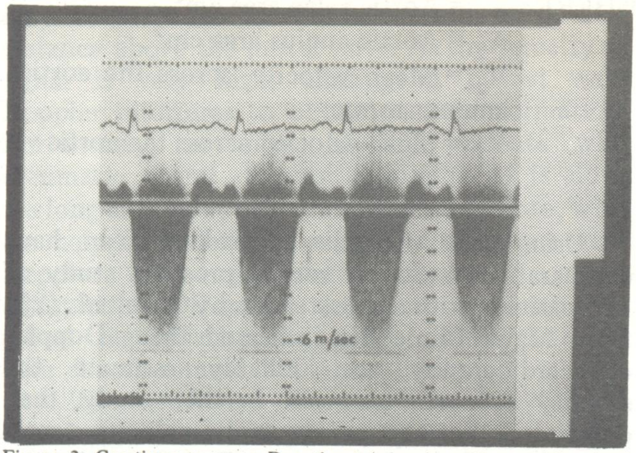

Figure 3. Continuous wave Doppler tracing in patient with mitral regurgitation (Apical view).

QUANTITATION OF AORTIC REGURGITATION

It is important to appreciate that the magnitude of any regurgitant jet velocity (aortic, mitral, or tricuspid) doesn't reflect the severity of the lesion. Infact, the high velocity jet of aortic regurgitation is due to the high diastolic gradient between the left ventricle and aorta. Like mitral regurgitation several semiquantitative methods have been used to assess the severity of aortic regurgitation.

1. Doppler mapping of the regurgitant jet in the left ventricle.
2. The deceleration rate of aortic regurgitant velocity.
3. Color flow mapping.
4. The strength of the regurgitant jet wave form.
5. The ratio of retrograde/antegrade flow in the descending aorta.

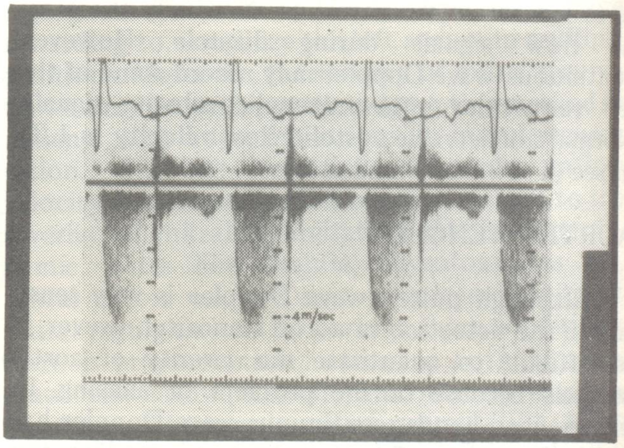

Figure 4. Doppler tracing recorded from the apical view in a patient with aortic stenosis. The peak velocity across the aortic valve is 4.2 m/sec with a peak instantaneous gradient of 71 mm Hg.

The widely used method out of these is mapping of the aortic regurgitant jet, described by Ciobanu, et. al. (26). The grading of aortic regurgitation is based on the linear extension of the jet into the left ventricle. Aortic regurgitation was grade 1 (mild) when the diastolic jet was restricted to the distal part of the left ventricular outflow, or just below the aortic valve, grade 2 (moderate), when the jet extended up to the anterior mitral leaflet. Grade 3 (severe) aortic regurgitation was indicated by the extension of the jet into the left ventricle distal to the mitral leaflet.

The other semiquantitative method which can be readily utilized to assess the severity of aortic regurgitation is the deceleration time of the regurgitant jet. At the onset of diastole, left ventricle-aortic gradient is maximum. The reduction of the gradient, besides other factors, depends on the severity of aortic regurgitation. The slope of deceleration time is inversely proportional to the severity of aortic regurgitation. Based on pressure half time (discussed in previous section) Teague, et.al. (27) using continuous wave Doppler, could quantitate the severity of aortic regurgitation. Patients with

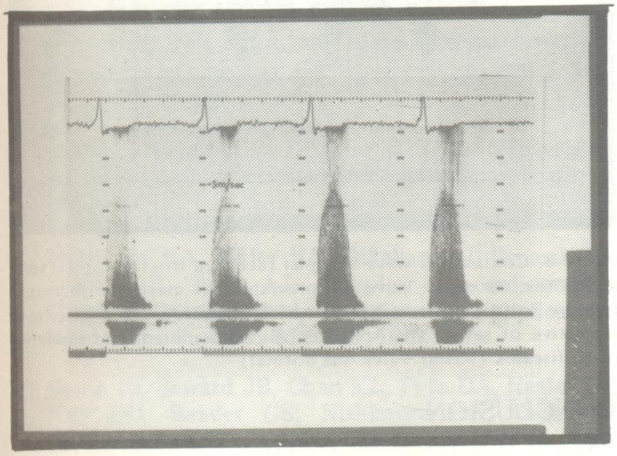

Figure 5. Continuous wave Doppler tracing in a patient with severe aortic stenosis recorded from the suprasternal view.

pressure half time < 400 m/sec was suggestive of having significant aortic regurgitation. However, in patients with left ventricular dysfunction there may be overestimation of severity of aortic regurgitation. Recent studies by Gilbert, et. al. (28), using color flow mapping has pointed out the limitations and poor correlation of the linear mapping of regurgitant jet. They suggested that the width of the regurgitant jet (not the jet length) at its origin (in parasternal short axis view) relative to the left ventricular outflow tract had excellent correlation with angiography. Several other methods like diastolic reversal of flow in the descending aorta (29, 30) and valvular regurgitant fraction (31,32) are also used to assess the severity of aortic regurgitation. In a recent study of 106 patients, (34) by Paul A. Grayburn, et. al., evaluated the accuracy of various noninvasive methods to detect aortic regurgitation. They found sensitivity and specificity of 96% and 96% for pulsed wave Doppler and 73% and 92% for clinical auscultation. They detected aortic regurgitation by pulsed Doppler in 19 patients without murmur. They concluded that of all the non-invasive techniques, Doppler echocardiography is the most sensitive in detection of aortic regurgitation.

TRICUSPID VALVE

Normal tricuspid valve flow pattern resembles that of the mitral valve, except that it has low velocity and shows phasic changes with respiration. Tricuspid valve can be examined with pulsed wave Doppler from the apical position or in a difficult case, from the subxiphoid view. Continuous wave Doppler is best used in the low parasternal position with a posterior directed beam. Using audiovisual signals continuous wave Doppler beam can also be directed across the tricuspid valve from the apical view.

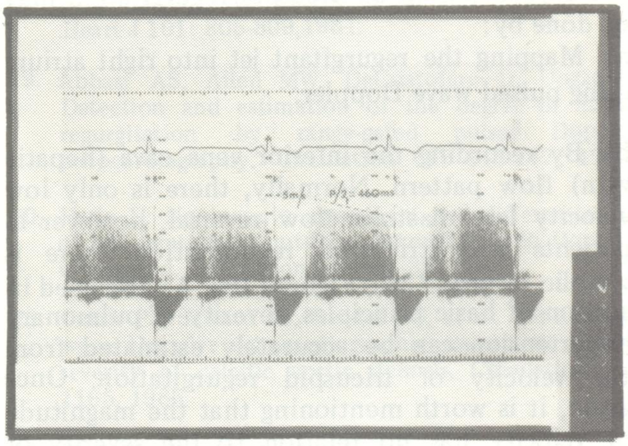

Figure 6. Continuous wave Doppler study across the aortic valve recorded from the apex. It shown a high velocity (4.8 m/sec) regurgitant jet with a pressure halftime (P/2t) of 460 milliseconds suggestive of mild aortic regurgitation.

Normal tricuspid flow velocity is 0.50 (0.3 - 0.7) m/sec in adults.

TRICUSPID REGURGITATION

Although primary rheumatic tricuspid regurgitation is rare, tricuspid regurgitation, secondary to pulmonary artery hypertension is not uncommon. In tricuspid regurgitation, there are systolic flow signals starting with the tricuspid closure below the zero line (from apical view). As a diagnostic criteria for tricuspid regurgitation, these signals should be pansystolic or occupy more than half of the systole. This is important because short systolic (early systolic) signals may be recorded due to normal tricuspid valve closure

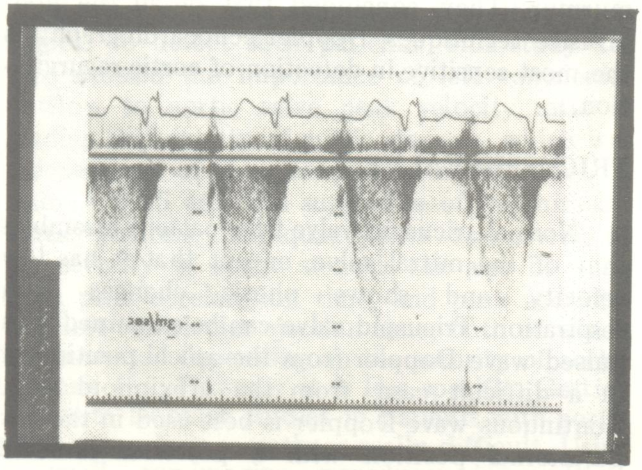

Figure 7 A. doppler recording across the tricuspid valve (apical viwe) in a patient with tricuspid regurgiation.

(35). Quantitation of tricuspid regurgitation may be done by:

a) Mapping the regurgitant jet into right atrium using pulsed wave Doppler.

b) By recording the inferior vena cava (hepatic vein) flow pattern. Normally, there is only low velocity late diastolic flow reversal, however in patients with tricuspid regurgitation there is systolic reversal (36), Figure (7B). As discussed in section of basic principles, severity of pulmonary hypertension can be accurately estimated from the velocity of tricuspid regurgitation. Once again, it is worth mentioning that the magnitude of velocity has no relation to the severity of tricuspid regurgitation.

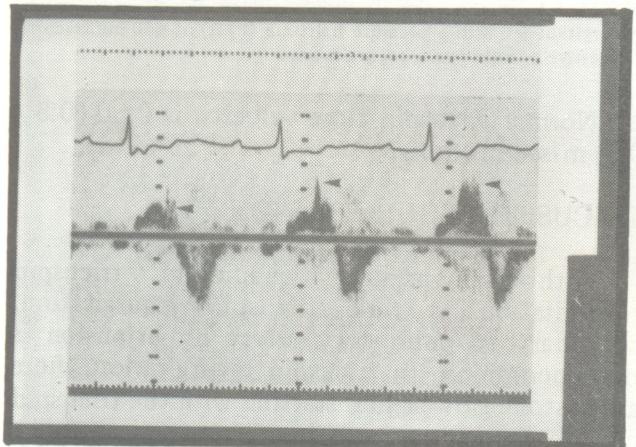

Figure 7B. Pulsed wave Doppler tracing of hepatic vein (subcostal view) from the same patient. Note the prominent systolic reversal (arrow heads) suggestive of tricuspid regurgitation.

TRICUSPID STENOSIS

The flow changes detected by Doppler in tricuspid stenosis resembles mitral stenosis, i.e., there is increase in the diastolic velocities with reduced pressure half time. However, changes are less severe and are markedly exaggerated with inspiration. Figure (8) demonstrates tricuspid stenosis in patients with carcinoid heart disease.

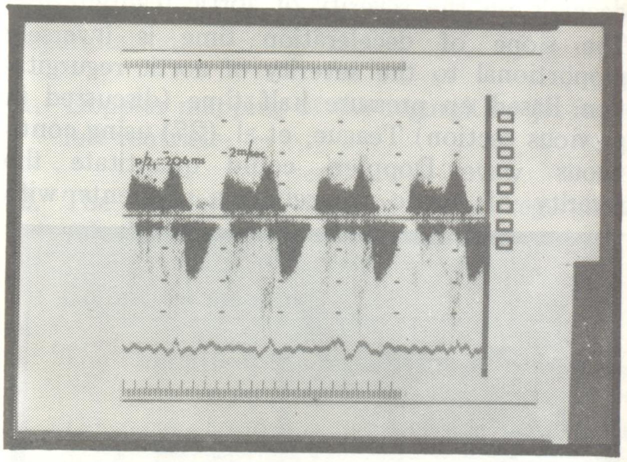

Figure 8. Continuous wave Doppler recorded from the apical view across the tricuspid valve. Appreciate the markedly increased pressure halftime (arrow heads) which measured 206 milliseconds suggestive of severe tricuspid stenosis. This patient had carcinoid heart diseases. (Mitral Valve was normal).

CONCLUSION

Doppler echocardiography has a profound influence on the clinical cardiology. It provides safe, non-invasive, reproducable and reliable cardiovascular hemodynamics. Majority of the patients in the developing countries, undergoing surgery for rheumatic heart disease, are still young and do not require preoperative coronary angiograms. As such, Doppler echocardiography, in adjunct to the color flow imaging can provide accurate hemodynamic data which is comparable with cardiac catheterization. Thus, Doppler echocardiography by replacing the invasive procedures in rheumatic heart disease can have a great impact on the technology and economy of the developing countries. However for the best results, it is necessary to integrate the data with the clinical and other non-invasive parameters. Accuracy of the information, like other technology, has a learning curve and improves with experience.

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