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Clinical applications of Doppler echocardiography combined with two-dimensional cardiac imaginc - A review

In this review, we have demonstrated the normal patterns of flow and some quantitative applications of Doppler echocardiography combined with two-dimensional imaging. Flow information can be accurately measured and valve gradient calculations can be made in patients with stenotic disease. Further corroborative work in this area is necessary before definitive statements can be made, but this appears to be a promising noninvasive technique which can be applied at the bedside or in an ambulatory setting with a fair degree of confidence.

To date, cardiac output measurements have primarily been accomplished by invasive procedures including cardiac catheterization, thermodilution catheters in intensive care units, or contrast angiography. These methods allow quantification of intracardiac and intravascular blood flaw, but carry the attendant problems of expense, some morbidity and potential mortality. Echocardiography allows volume and output estimation but development of more accurate noninvasive methods for accomplishing this same purpose is desirable.

The purpose of this review is to provide a status report about new techniques for Doppler echocardiography which show promise for accurate noninvasive characterization of normal flow[1-4], calculation of cardiac output[5-9] prediction of severity of valvular disease[10-20] and shunt quantitation[21-29].

Physics and instrumentation in doppler echocardiography

The Doppler effect implies that sound frequency of reflected sound is altered when the sound source or target is moving . Christian Johan Doppler, an Austrian physicist, was first to demonstrate this effect.

This changes in frequency is called “Doppler frequency shift”. Since flowing blood contains particulate material, mainly red blood, cells, these can serve as a target for reflection or scattering of ultrasound. The Doppler shift infrequency will be proportional to the velocity of cell motion. Reflected ultrasound is received at an angle (0) from the transducer placed cm the skim, and the change in frequency between transmitted (f_0) and reflected (f_1) ultrasound cam be measured. This relationship, wich translates ultrasound frequency into blood velocity, is expressed by the Doppler equation: blood flow velocity =

$$\frac{(f_1 - f_0) \times \text{velocity of sound in blood}}{2f_0 \times \cos\Theta}$$

(where velocity of sound in blood = 1540 m/sec, f_1 = reflected ultrasound, f_0 = transmitted frequency, and $0 = 1$ angle between the assumed direction of flow and the Doppler sampling direction. The numerator is divided by two because sound travels from and to the transducer.)

Two types of Doppler instrumentation are commonly used in medical applications: continuous wave Doppler and pulsed Doppler. Continuous wave Doppler uses a constant transmission and reception of ultrasonic signals and has the advantage of measuring very high maximal velocities. In pulsed Doppler sequentially transmitted bursts of ultrasound are emitted over time. The advantage of pulsed Doppler is that the signal can be range gated that is, a

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period of time during the returning cycle corresponding to a specific structure to be interrogated to the exclusion of others can be selected, allowing measurement of velocity in that small area at a selected depth along the ultrasonic beam. Continuous wave Doppler does not allow range gating. However, pulsed Doppler limits the maximal velocity which can be recorded unambiguously.

When pulsed Doppler is used, the region where flow is sampled is called the sample volume. The sample volume shape is variable depending upon the type of instrumentation utilized. The width is determined by beam width characteristic of the transducer, whereas the axial length may be adjustable or fixed, depending upon the instrument used.

Positioning of the sample volume is facilitated by combining the Doppler examination with an echocardiographic examination. Early phinstrumentation used M mode echocardiography, but the present state of the art incorporates Doppler with two-dimensional echocardiography. This allows placement of the sample volume into various chambers or vessels and permits determination of tile angle (θ) between the sample volume and flow within that vessel or cavity for quantitation of flow. The Doppler velocities are measurable by spectral analysis. This method relies upon fast Fourier transform analysis to yield a signal composed by Doppler shifted frequencies which allows a linear display of the frequencies.

When flow thorough a cardiac chamber, valve orifice or great vessel is smooth and uniform, red cells generally move in a parallel fashion. The shape of the flow wavefront can be flat or parabolic, depending upon vessel diameter. Generally, flow is laminar. When flow is disturbed, as occurs in some cardiac lesions such as valve stenoses, red cells scatter as the jet vortices shed and the corresponding Doppler shift will be composed of widely distributed frequencies. This is termed "disturbed" flow. Characterization of laminar or disturbed flow was made in the early Doppler literature to qualitatively describe lesions which were associated with vortex shedding.

The instrumentation which we have primarily used for quantification of cardiac output, shunt measurement and valve gradient measurements is a two-dimensional mechanical sector scanner,(E for M/Honeywell), with pulsed Doppler. This instrument can be operated in three modes; 1) a two-dimensional image with movable cursor for sample volume positioning and angle determination; 2) pulsed Doppler output derived from the position selected by the cursor. This Doppler signal is submitted to fast Fourier transform to analysis provide linear velocity information; 3) simultaneous M-mode and pulsed Doppler outputs are available. A lead II electrocardiogram may be displayed for time reference. This instrument allows selection of various frequency transducers (3.5 and 5 MHz). These can be mechanically oscillated over a sector angle range from 30 to 75 degrees sector angle. The same transducer can be utilized for all three modes Sample volume cam be varied to a maximal depth of 12 cm from the transducer and cam be varied in axial length from 2 mm to 2 cm. Doppler pulse frequency is 13,000/sec when a signal is obtained from a depth less than 6 cm, 7800 samples/see when it is beyond 10 cm. The respective maximal velocities that cam thus be recorded are 143, 85, and 52 cm/sec. Images are displayed on a oscilloscopic monitor in real-time at 30 frames/ sec. Selected frames cam be printed on a combination strip chart page print recorder (Honeywell LS8). A cursor is used to fallow sample volume placement. Signals are displayed on an oscilloscopic monitor which has sweep speeds of up to 100 mm/sec. Data can be recorded on video tape and hard copy. The systems computer allows automatic determination of angle between flow and transducer sample volume interrogation.

The second instrument is a 2-5 MHz phased array two-dimensional sector scanner which allows choice of either pulsed or continuous wave Doppler (Irex system 3-A). This instrument allows simultaneous visualization of two-dimensional image on one monitor and Doppler or M-mode outputs on another monitor. The sample volume can be moved only in the vertical axis on the two-dimensional image, and has a fixed 2 x 4 nun size. Doppler outputs can be displayed in three simultaneous modes, 1) digital spectrum velocity, 2) analog velocities (mean and maximal), and 3) integral velocities (mean and maximal). Two-dimensional echo and Doppler outputs can be simultaneously recorded on video monitors and selected frames. The system's computer determines angle between flow direction and the Doppler beam.

Examination technique

A standard two-dimensional echocardiographic examination is performed first[2]. The Doppler examination then includes samples volume interrogation of the following areas: Right atrium, tricuspid outflow, right ventricle, tricuspid outflow, right ventricular body, right ventricular outflow tract, pulmonary valve area, main pulmonary artery area, left atrium, body and mitral valve inflow, left ventricle, mitral valve outflow, left ventricular outflow tract, aortic valve area, aortic root, and suprasternal ascending and descending aorta. Several echocardiographic planes can be utilized for sampling various areas. For example, the apical two-chamber plane allows interrogation of the mitral inflow and outflow, left ventricular outflow, aortic root, and part of the ascending aorta. Subcostal planes allow interrogation of either side of the atrial septum and short axis

views are best for pulmonary outflow and pulmonary artery measurement. An important principle is that the interrogation beam angle (0) should be as close as possible to 0° or 180°, with reference to flow.

Normal flow patterns

Right atrial and right outflow tract -Tricuspid valve inflow and outflow cam be best imaged when the transducer is held in a standard apical four chamber position. Velocity transducer is held in a standard apical four chamber position. Velocity values of flow through the tricuspid valve parallels the pattern of the tricuspid valve itself, with an initial forward peak in early diastole (rapid ventricular filling phase) followed by velocity deceleration which continues until atrial contraction, resulting in a small forward peak. Forward flow is generally not detectable during systole. Diastolic velocity is increased during inspiration in most children; however, this is no necessarily the case in newborns, who have a short diastole period. Most tricuspid velocities are best detected in the right ventricular inflow tract. Flow in the right atrial body is generally of slight magnitude (fig. 1A).

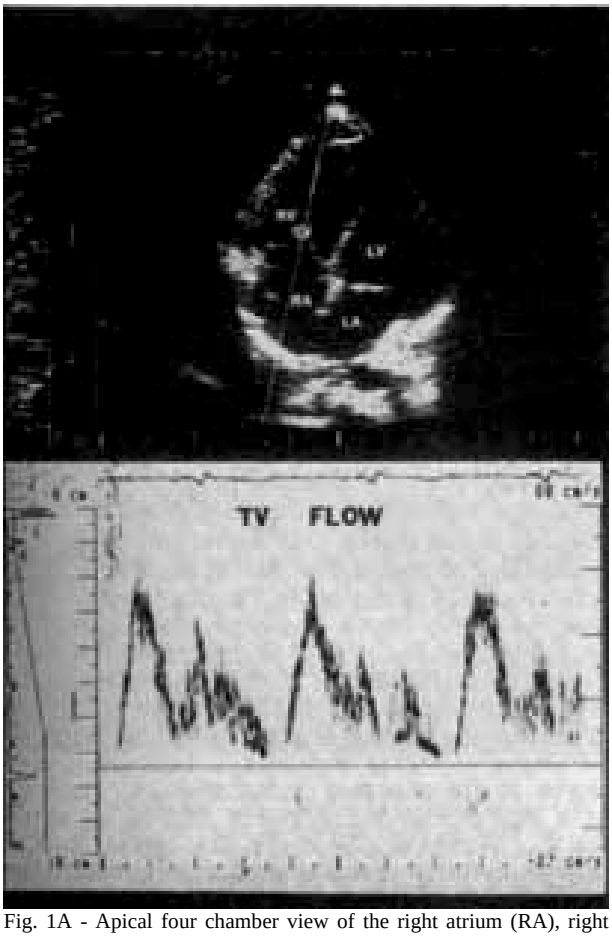

Fig. 1A - Apical four chamber view of the right atrium (RA), right ventricle (RV), left atrium (LA), and left ventricle (LV) with the sample volume (SV) positioned along the direction of flow into the right ventricle. Doppler velocity output derived from that sample site is shown below. The peak velocity record is 60 cm/sec as measured from the ordinate on the right. This is a typical triscupid valve flow pattern (TV FLOW).

Pulmonary outflow tract - This area is best sampled with the transducer in the parasternal short axis plane and the sample volume placed either proximal or distal to the pulmonary valve. Since systolic flow Is away from the transducer, it is detected as negative. The diastolic pattern is generally random but in some children with slow heart rates, some diastolic flow can be detected during inspiration (fig. 1B).

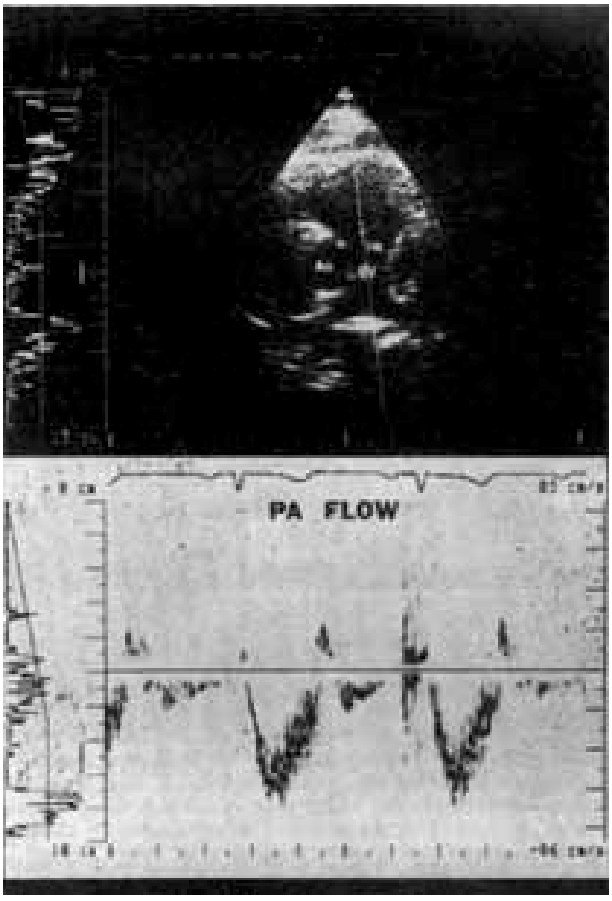

Fig. 1B - Parasternal short axis view of the aorta (AO). Pulmonary artery (PA) and PA branches. The sample volume (SV) is positioned in the main PA along the direction of flow. Doppler flower velocity derived from that sample site is shown below. The peak velocity away from the transducer recorded id - 70 cm/sec. This represents a normal pulmonary flow (PA FLOW) pattern.

Mitral Inflow and outflow tract - Mitral inflow and outflow velocities are best detected from the apical two-chamber plane, apical four chamber plane, and are less well detected in parasternal long and short axis planes because of transducer angulation.

Left ventricular inflow is best detected below the mitral valve and the flow pattern is reminiscent of the mitral echo pattern and the tricuspid pattern already described (fig. 1C). Usually, very little flow activity is detected in the. left atrial body itself. This may be due to law flow velocity from the pulmonary veins into the left atrium and also due, to the distance of the left atrium from the sampling transducer.

Left ventricular outflow tract - Flow in the left ventricular outflow tract is best detect-

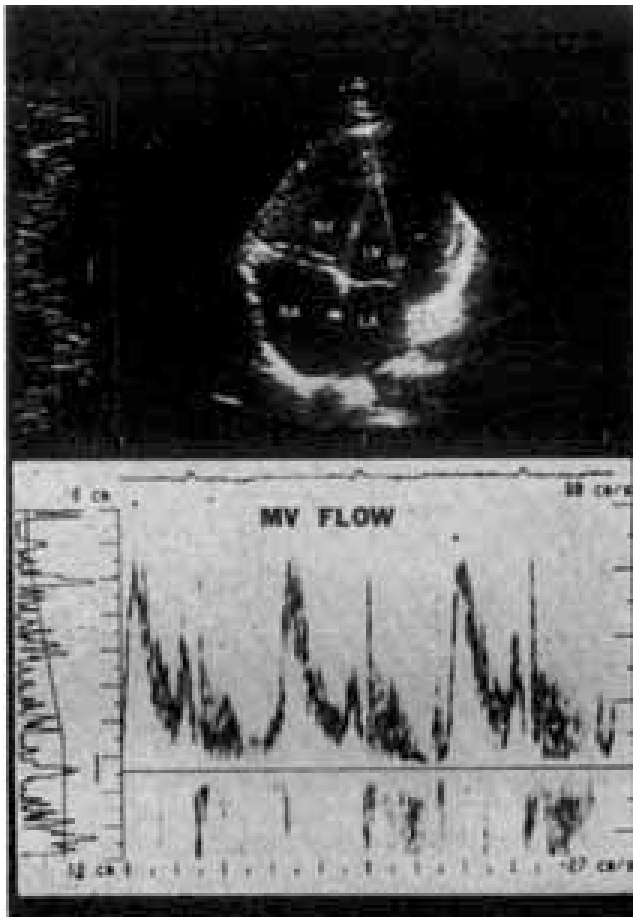

Fig. 1C - Apical four chamber view of the right atrium (RA), right ventricle (RV), left atrium (LA), and left ventricule (LV) with the sample volume (SV) positioned along the direction of flow into the left ventricule. Doppler velocity output derived from that sample site is shown below. The peak velocity recorded is 60 cm/sec (normal). The closure spike of the mitral leaflets is also detected. Mitral valve flow (MV FLOW) closely resembles the pattern of movement of the mitral leaflet on M-mode echocardiography.

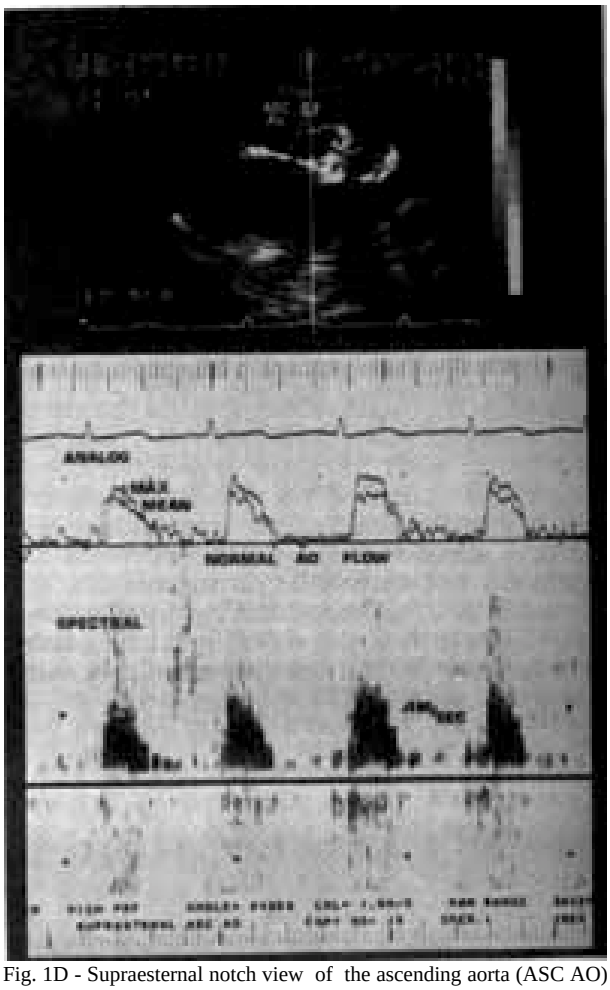

Fig. 1D - Supraesternal notch view of the ascending aorta (ASC AO) with the sample volume placed along the direction of flow in the ascending aorta. Doppler velocity output derived from that sample site is shown below. The top curves represent the analog output of the maximal (MAX) and mean velocities. The bottom curve display is the Doppler spectral signal. The peak velocity is 120 cm/sec. This pattern of flow represents normal aortic flow.

ed with the transducer in either the apex four or two-chamber position, and can also be detected with the transducer in the subcostal position if the interrogation angle is not approaching the perpendicular. Since flow is away from the transducer (in the apex plane), a negative deflection is noted during systole. With the sample volume moved through the aortic valve plane from the suprasternal notch, leaflet motion can be detected. When the aortic root is Interrogated, forward flow is noted during systole and some reverse flow is detected during diastole (probably representing coronary flow).

Ascending aorta, descending aorta - The aortic arch is best evaluated from the suprasternal notch view. Systolic flow is toward the transducer when the ascending aorta is interrogated (fig. 1D), and is away from the transducer when the descending aorta is interrogated. Velocities are higher than those seen in pulmonary artery. Diastolic flow is generally not detected in the descending aorta.

Clinical applications

Cardiac output measurements - A major application of two-dimensional echocardiography in pulsed Doppler is flow quantification. This can be achieved using the equation: SVD = (mean V x CSA x RR interval)/cos 0 where SVD is stroke volume by Doppler, mean V = mean velocity, CSA = cross-sectional area of the vessel or valve, cos 0 = cosine of the angle between the Doppler beam and direction of the flow). Two of the variables are derived from the two-dimensional image. The first one is the angle 0. This presents a limitation with regard to its accurate measurement, since an angle in the third dimension cannot be determined. However, because the cosine of the angle 0 is utilized in the equation, variations in angulation of up to 25 º are so small that they cause insignificant calculation errors. The second variable is the cross-sectional area of the vessel (CSA) in question. This can be obtained by measuring the vessel diameter and converting it into area by using the following equation: $CSA = \pi 1/ d d)^2$ (where d = vessel diameter). Mean velocities can obtained by measuring the area under the Doppler velocity curve from

successive beats on the spectral display using a desk-top digitizing system. Multiplying the result of equation 1 times the heart rate allows quantification of cardiac output.

Shunt quantitation - Recent work by our group [23,24] has demonstrated that pulmonary flow (QP) and systemic flow (QS) in patients with various congenital cardiac and extracardiac shunts (atrial septal defects, ventricular septal defects, patent ductus arteriosus) and in animals with surgically-created shunts, can be accurately quantified, allowing shunt determination. Most cardiac flow measurements are based upon measurement of aortic flow or pulmonary artery flow. In order to overcome some of the errors in calculation of pulmonary flow, which is disturbed, especially in patients with cardiac shunts, we developed the mitral valve orifice method[7]. In our laboratory, excellent correlation was found between noninvasive estimates of cardiac outputs in animals with electromagnetic flow meter correlations and in humans with thermodilution. Measurement. This method is based upon interrogation of the mitral area from the two-dimensional parasternal short axis plane and multiplied in this area by an average opening factor obtained from the derived M-mode tracing. The Doppler mitral flow is obtained from an apical four chamber view (fig. 2). Pulmonary (QP) and systemic (QS) blood flows may be calculated in different cardiac sampling sites according to the type of lesion as follows:

Transvalvar gradient - Another quantitative application of the Doppler method is measument of

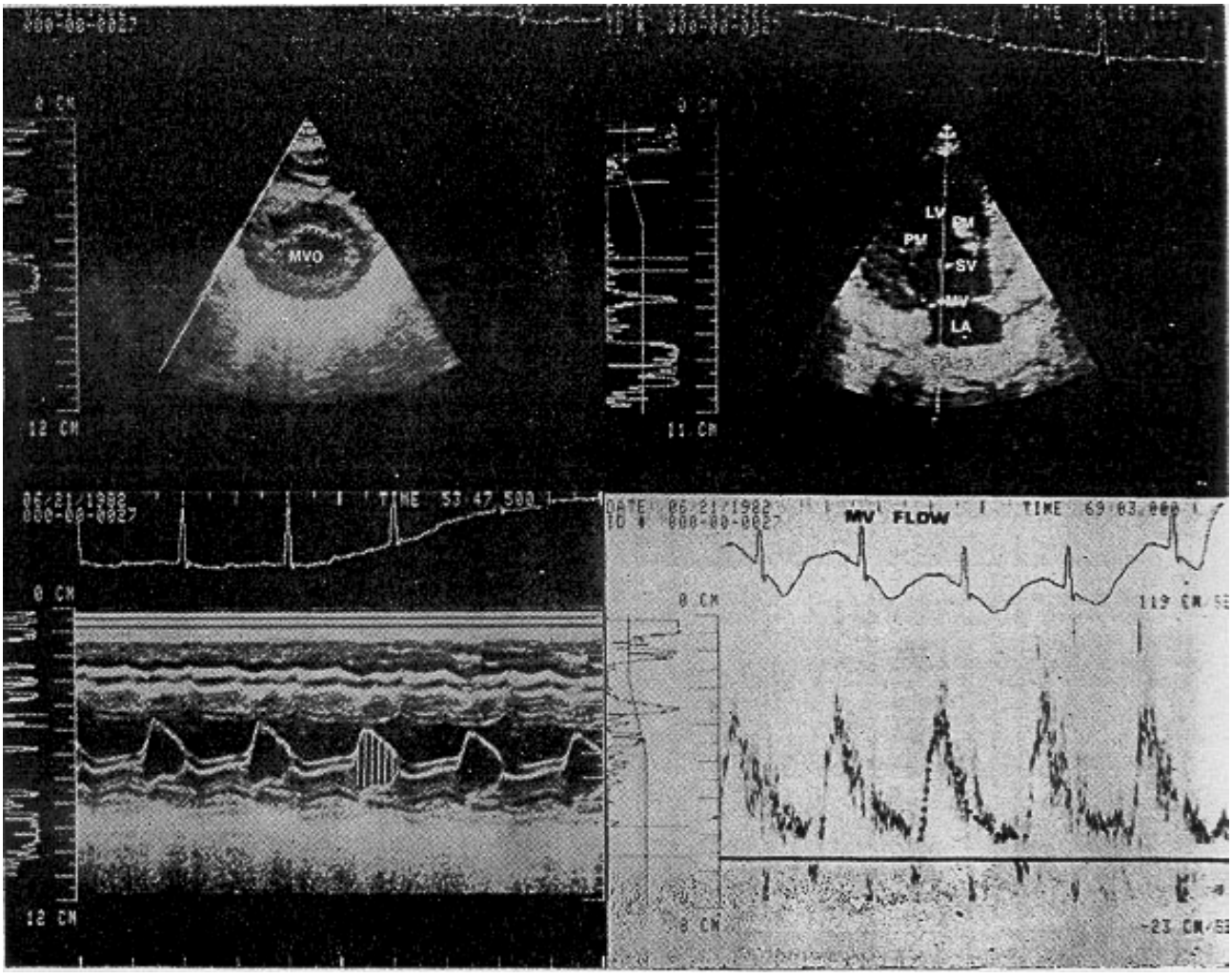

Fig. 2 - Paraesternal short axis view of the mitral orifice (MVO). Maximal mitral valve orifice is obtained by gating the real-time two-dimensional image to maximal opening from a derived M-mode trace and simultaneous electrocardiogram. The mean diastolic mitral orifice is determined by examining the mitral M-mode pattern (see text for details). Flow is then sampled from an apex view by poistioning the Doppler sample volume in the left ventricular inflow. Doppler velocity evidence of significant spectral dispersion. LV = left ventricule; PM = papillary muscle; SV = sample volume; MV = mitral valve; LA = left atrium; MV FLOW = mitral flow.

Lesion	ASD	VSD	PDA
QP	Pulmonary artery	Mitral valve	Mitral valve
QS	Aorta or mitral valve	Aorta	RVOT

pressure gradient through stenotic valves. This is accomplished by application of simplification of the Bernoulli equation as described by Hatle et al [14,19,20]. In this equation, the maximal velocity of flow distil to the ste-

notic valve orifice in the area of greatest vortex shedding is squared and multiplied by a constant, 4 ($VG = V^2 \times 4$) (where VG = valve gradient, V = maximal velocity).

Examples of quantitative applications of doppler echocardiography

Shunt Quantitation

Patent ductus arteriosus - A patent ductus arteriosus can be visualized by two-dimensional echocardiography[29]. The flow characteristic cannot be determined. The shunt through a patient ductus arteriosus can be left-to-right, right-to-left, or bi-directional. Accordingly, quantitation of flow may be important clinically in these patients. With the sample volume placed in the pulmonary, we can detect the high velocity flow toward the transducer during diastole (fig. 3) This pattern of flow can be found even when patient ductus arteriosus is associated with other forms of congenital heart disease. In children with patent ductus arterious, the systemic flaw (QS) is calculated as the systemic venous return in the subpulmonic region of the right ventricular outflow tract. Since some blood in the ascending aorta is diverted through the ductus arteriosus into the pulmonary circulation, and the main pulmonary artery, which exhibits multidirectional flow patterns may mot reflect total pulmonary flow, pulmonary flow calculation (QP) in these cases is obtained from the mitral valve site.

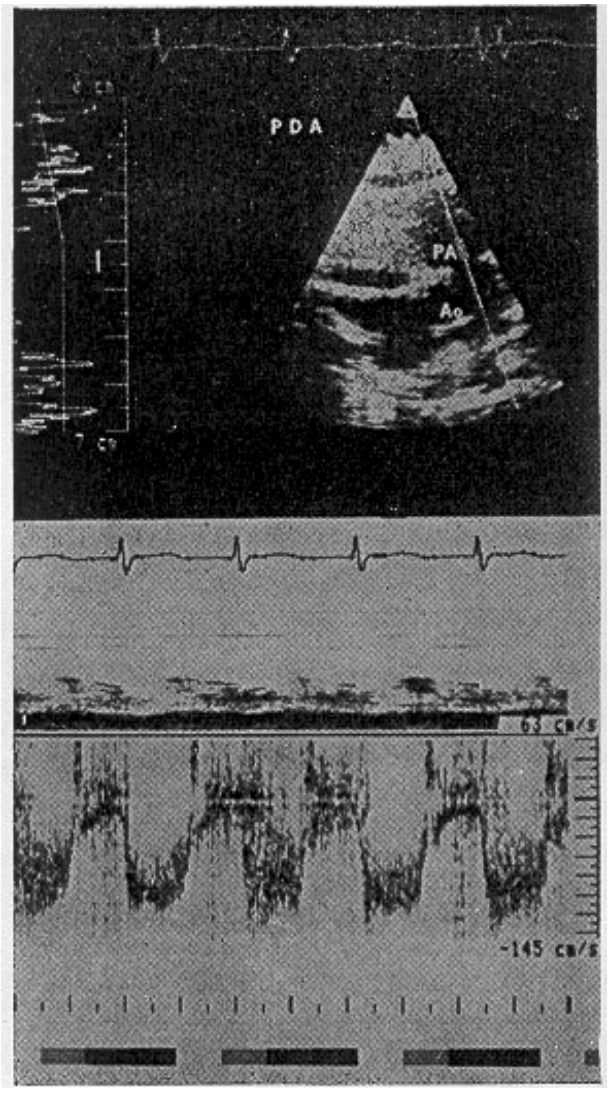

Fig. 3 - Paraesternal short axis view the pulmonary artery (PA) and aorta (AO) with the sample volume placed along the direction of flow in the main pulmonary artery. The derived Doppler flow is shown below and represents the patterns of flow found in patients with patente ductus arteriosus. Note the abnormal pattern of flow detected in the pulmonary artery during systole and diastole.

Transvalvar gradients

Pulmonary stenosis - Echocardiography (M-mode and two-dimensional) are useful techniques to provide diagnosis of pulmonary stenosis. However, they do not allow prediction of severity of stenosis or of transvalvar gradient. Doppler echo has been reported as a good technique for quantifying severity of stenotic valvar lesions [12,14,18,19,20]. The simplified Bernoulli equation is applied to spectral outputs derived from the continuous wave Doppler, since pulsed wave velocities exceed the limit frequency (Nyquist frequency). In a recent study from our laboratory [12], good correlations were found between Doppler maximal velocity ($r = 94 \pm 51$ cm/sec) and Doppler estimated pressure gradients ($r = 98 \pm 7$ mm Hg) and transvalvar gradients measured at cardiac catheterization (fig. 4).

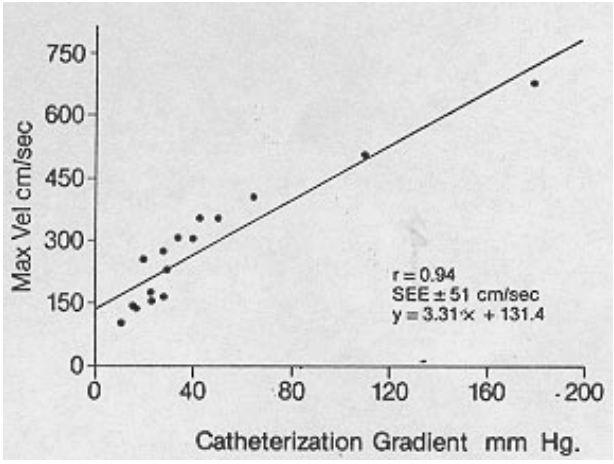

Fig. 4A - Regression line comparing pulmonary maximal velocities (MAX VEL in cm/sec) in patients with pulmonary stenosis with the pressure gradients obtained by invasive techniques (mm Hg).

Briefly the ultrasonic examination begins with two-dimensional echocardiographic parasternal short axis view imaging of the right ventricular outflow tract, pulmonary valve, maim pulmonary artery and bifurcation. The sample volume is placed in the center of the pulmonary artery distal to the domed pulmonic valve leaflets in line with the apparent orifice. The maximal velocity is found and recorded by varying the position of the sample volume within the pulmonary artery until the maximal audible signal identified as a whistle is achieved and

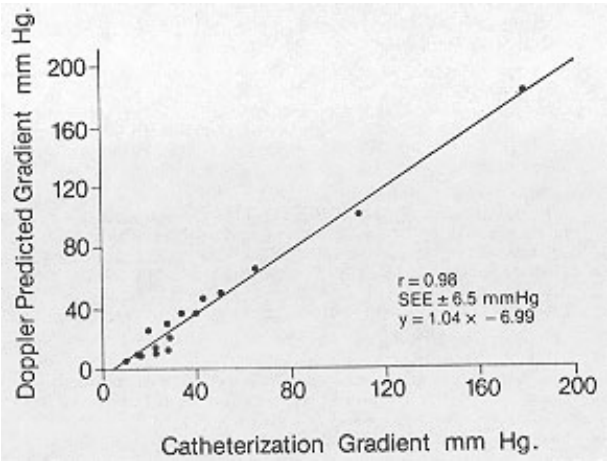

Fig. 4B - Regression line comparing Doppler-predicted pressure gradient (simplified Bernoulli equation) with the pressure gradient obtained by catheterization in patients with pulmonary stenosis. See text for details.

the maximal graphic output is then recorded. Usually, the angle of sample volume and direction of flow was 0° (parallel). The recorded peak systolic flow velocities from two to there consecutive beats were to transvalvular gradients using the simplified Bernoulli equation ($VG = V^2 \times 4$) (fig. 5).

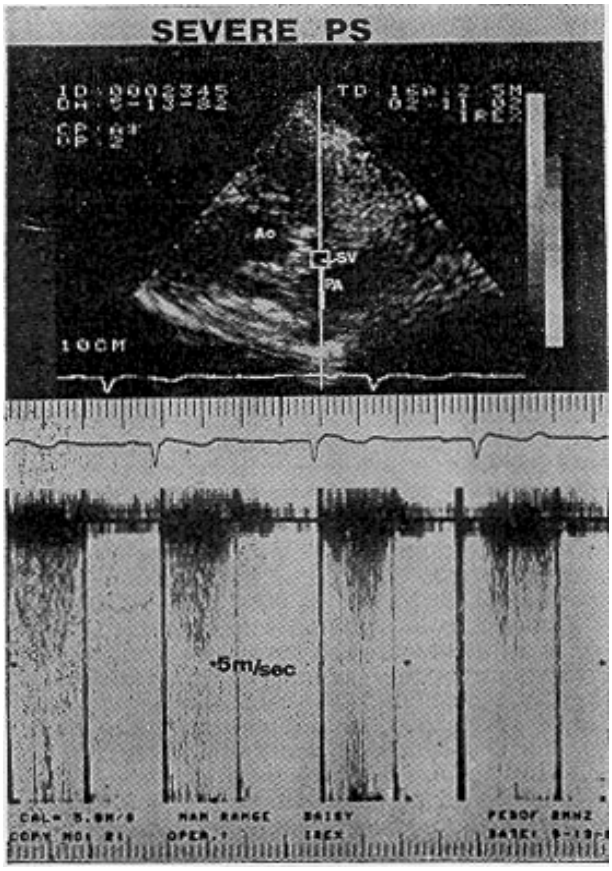

Fig. 5 - Paraesternal short axis view of the aorta (AO) and pulmonary artery (PA) with the sample volume (SV) positioned in the main pulmonary artery. Peak flow velocity of 500 cm/sec was detected in this patient with severe pulmonic stenosis (PS). The estimated pressure gradient at catheterization was 110 mm Hg.

RESUMO

No presente artigo procuramos descrever os conceitos básicos bem como demonstrar os padrões normais de fluxo através das diferentes valvas cardíacas obtidos por meio da ecocardiografia Doppler combinada com imagem cardíaca obtida através da ecocardiografia bidimensional. Também descrevemos as mais recentes aplicações clínicas dessa nova modalidade diagnóstica. Enfoque especial foi dado a quantificação de fluxo, isto é, medida estimava do óbito cardíaco e "shunts" esquerda-direita, bem como estimativa não invasiva gradientes pressóricos em pacientes acometidos de lesões valvares tipo estenose.

Enquanto maior experiência se faça necessária para aquisição de conceitos definitivos, essa recente metodologia parece oferecer um novo campo para obtenção de dados de grande aplicabilidade clínica.

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