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Echocardiographic haemodynamic calculations

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Introduction

Echocardiography provides a non-invasive (transthoracic echocardiography [TTE]) tool that can be used to assess cardiac function. Transoesophageal echocardiography (TEE), although not as benign as TTE, is vital in the diagnosis of vital and subtle cardiovascular abnormalities.

Echocardiography affords the user the opportunity to assess anatomical structures and functional parameters. Importantly, haemodynamic measurements are made using 2D echocardiography and Doppler measurements.

Echocardiography can be used to determine quantitative and qualitative parameters of the heart regionally and globally. Additionally, subjective assessments of the heart function can be made in a perioperative setting that can assist with clinical intervention. Volumetric measurements, pressure gradients, valve area, intracardiac pressures and ventricular dp/dt can all be determined.

Qualitative assessment

This method is used to visually make assessments of structure and function without measurements. The method is used commonly in the clinical setting and may assist with initial analysis (Figure 1).

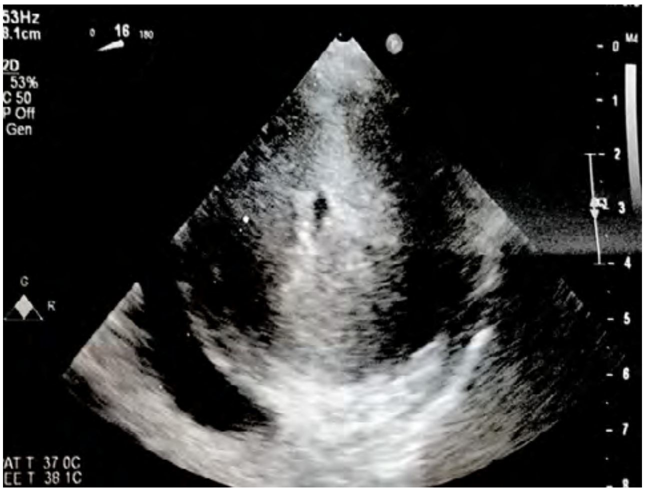

Figure 1: Overt pathology seen on qualitative observation

Quantitative assessment

Quantitative assessment can be used to determine volumes, ejection fraction, fractional shortening, and fractional area change. These are load-dependent indices that are affected by preload and afterload. In addition, Doppler is used to measure flow velocities and intracardiac pressures. The assumption made in measurement of flow velocities is that flow is laminar and flowing in a constant area parallel to the ultrasound beam with a flat flow velocity profile.

Cardiac output

Cardiac output is determined as a product of stroke volume (SV) and heart rate (HR). SV is a difference between end-diastolic volume (EDV) and end-systolic volume (ESV). SV in echocardiography takes into consideration the 3D nature of the ventricle and therefore is determined as a product of velocity time integral (VTI) and cross-sectional area (CSA) (Figure 2).

$$CO = SV \times HR$$

$$CO = CSA \times VTI \times HR$$

Cross-sectional area derived from the 2D image on echocardiography is determined from the diameter.

$$CSA = \pi r^2$$

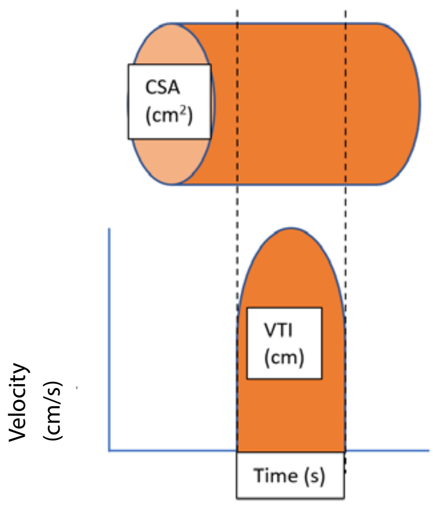

Figure 2: Diagrammatic illustration of CSA and VTI

$= \pi\ (D/2)^2$

$= 0.785 \times D^2$

To obtain relatively accurate SV Doppler calculations, VTI measurement are repeated 3–5 times in sinus rhythm and 8–10 in atrial fibrillation.[1] The reported measurement represents the average. The VTI Doppler beam should be parallel to flow and taken at the same location and time as the SV.[1]

Left ventricular cardiac output

This can be determined in three areas of the left heart: left ventricular outflow tract (LVOT), trans-aortic valve (Ao) and trans-mitral (MV) areas.[2]

LVOT SV

The diameter is measured in mid-systole from the mid-oesophageal (ME) long axis view (LAX) at the junction of AV cusp to septal myocardium anteriorly and anterior mitral cusp posteriorly (Figure 3A). The largest of 3–5 readings should be used. The VTI_{LVOT} is measured through the trans-gastric (TG) LAX or deep trans-gastric (DTG) LAX with the view of the outflow tract (Figure 3B). Pulsed wave Doppler is placed approximately 5mm proximal to the AV.[3]

Figure 3A: Aortic annulus and LVOT diameter ME LAX

Figure 3B: VTI through LVOT and Aorta TG LAX

Trans-aortic valve SV

The ME short axis (SAX) AV view is used to access the images of the heart. A CSA of the AV is determined by planimetry during mid-systole (open valve) (Figure 4A). Alternatively, CSA by cine-loop measurement of the length of a side of the equilateral opening of the AV valve is measured (Figure 4A), and CSA is calculated using the equation below:

$$CSA_{AV}\ (cm^2) = 0.433 \times (side)^3$$

Continuous wave Doppler through AV in TG LAX or deep TG LAX is used to measure VTI as above.

Figure 4A: CSA $_{AV}$ by planimetry

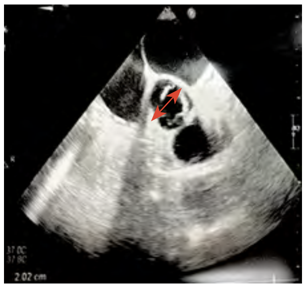

Figure 4B: CSA $_{AV}$ by cine-loop measurement of length of a side

Trans-mitral SV

The image is obtained in the ME four camber (4C) view. With pulsed wave Doppler, the VTI is determined at the level of the mitral annulus. The base of the anterior to posterior end of the annulus is measured during mid-diastole (Figure 5A). The annulus is an irregular semi-elliptical structure. Therefore, an unusual formula for measurement of CSA is used to accommodate this structure:

$$CSA\ _{MV}(cm^2) = 0.785 \times D_{MV}/D_{MV}{}^2$$

Figure 5B depicts the measurement of VTI_{MV} in the ME 4C view.

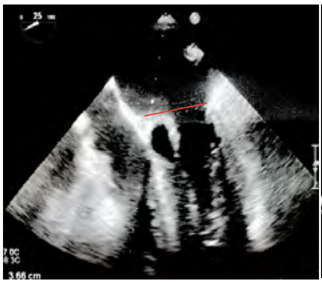

Figure 5A: CSA_{MV} during mid-diastole

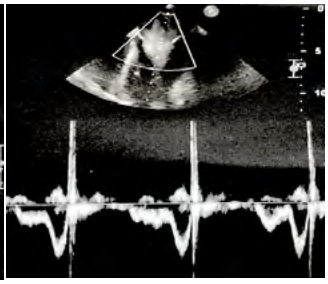

Figure 5B: VTI_{MV}

Right ventricular cardiac output

Right sided cardiac output is determined from pulmonary annulus (PA) and right ventricular outflow tract (RVOT).

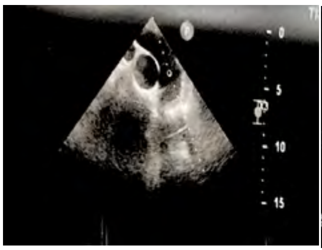

Figure 6A: The PA method of RV cardiac output determination

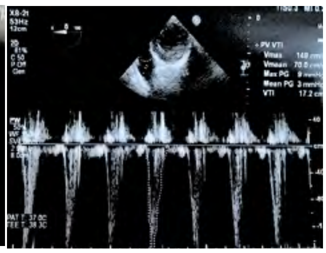

Figure 6B: The RVOT inflow outflow method of RV cardiac output determination

Ejection fraction, fractional shortening and fractional area change

The Simpsons method of discs is used to determine volumes as the traditional method of calculating ejection fraction (EF). EF can also be estimated from fractional shortening (FS) and fractional area change (FAC).[4] Figure 7A depicts the Simpson method, whilst Figure 7B depicts an image of the TG mid-papillary SAX view using M-mode to determine FS and, therefore, estimation of EF. The following calculations are used.

$$EF\% = [(EDV - ESV) / EDV] \times 100\%$$

$$FS\% = [(LVEDd - LVESd) / LVEDd] \times 100\%$$

Figure 7A: The Simpsons method of determining EF

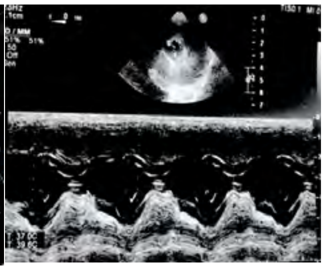

Figure 7B: M-mode method of determining EF

Fractional area change is also realised in the TG mid-papillary SAX view (Figures 8A and 8B). Through tracing of the endocardial surface in both end-systole and end-diastole, the area can be calculated.

$$FAC\% = [(LVEDA - LVESA) / LVEDA] \times 100\%$$

Figure 8A: Fractional shortening determined in the TG SAG

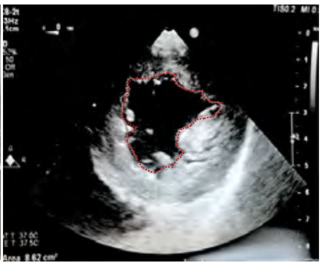

Figure 8B: Fractional shortening determined in the TG SAG

Estimation of regurgitant volume and fraction

Volumetric method

The principle used to determine regurgitant volume and fraction uses the notion that the SV entering the mitral valve is equivalent the SV leaving the aortic valve (Figure 9).

FLOW IN = FLOW OUT

$$SV_{SYSTEMIC} = SV_{TOTAL} - RV$$

$$RV = SV_{TOTAL} - SV_{SYSTEMIC}$$

$$RF\% = (RV/SV_{TOTAL}) \times 100\%$$

Mitral regurgitant volume and fraction

Regurgitation at the mitral valve dictates that SV_{MR} equals the SV_{LVOT} and RV_{MV} (Figure 10).

$$SV_{LVOT} + RV_{MV} = SV_{MVI}$$

$$RV_{MV} = SV_{MVI} - SV_{LVOT}$$

$$RF_{MV}\% = (RV_{MV}/SV_{MVI}) \times 100\%$$

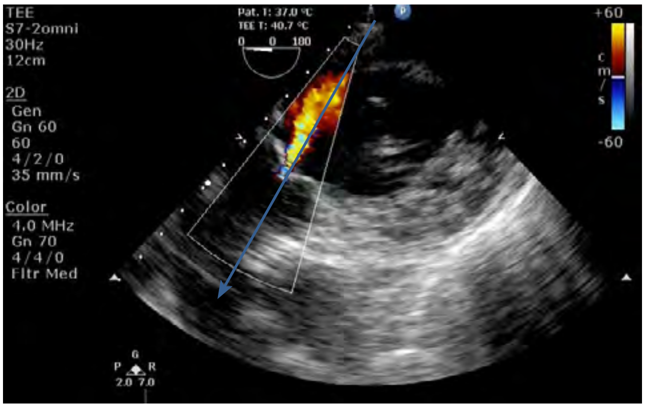

Figure 9: Aortic regurgitation

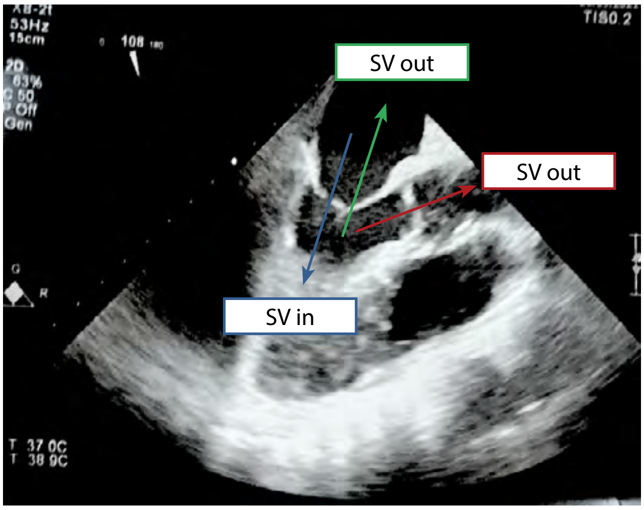

Figure 10: Mitral regurgitation

Aortic regurgitant volume and fraction

Similarly, in aortic regurgitation, the SV_{MR} and RV_{AV} equals the SV_{LVOT} (Figure 11).

$$RV_{AV} + SV_{MVI} = SV_{LVOT}$$

$$RV_{AV} = SV_{LVOT} - SV_{MVI}$$

$$RF_{AV}\% = (RV_{AV}/SV_{LVOT}) \times 100\%$$

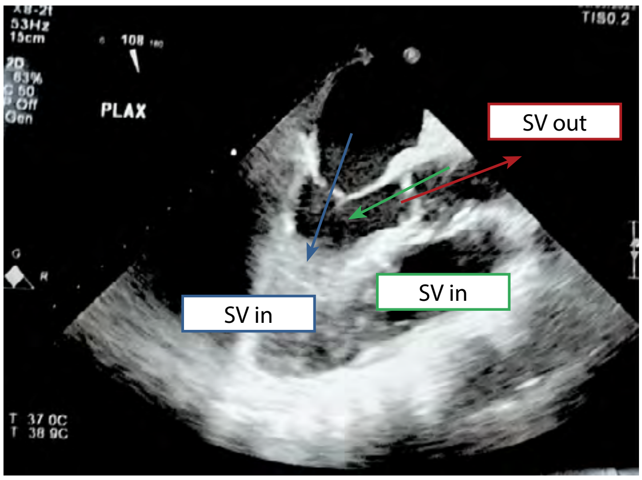

Figure 11: Aortic regurgitation

Proximal convergence method

This method of estimation of regurgitant volume is based on the principle of conservation of flow. Flow is the product of area and velocity. This method is used to estimate the regurgitant volume across the mitral valve by determining the flow rate through the PISA. The EROA is determined using this PISA flow rate and the peak velocity of the regurgitant flow/aliasing velocity (Figure 12).

PISA flow rate = PISA area x blood velocity

= 2π x r^2 x aliasing velocity

= 6.28 x r^2 x aliasing velocity

PISA flow rate = regurgitant flow rate

= EROA x regurgitant velocity

EROA = PISA flow rate / regurgitant velocity

EROA = (6.28 x r^2 x aliasing velocity) / V_{RJ}

RV = EROA x VTI

= (6.28 x r^2 x aliasing velocity / V_{RJ}) x VTI_{RJ}

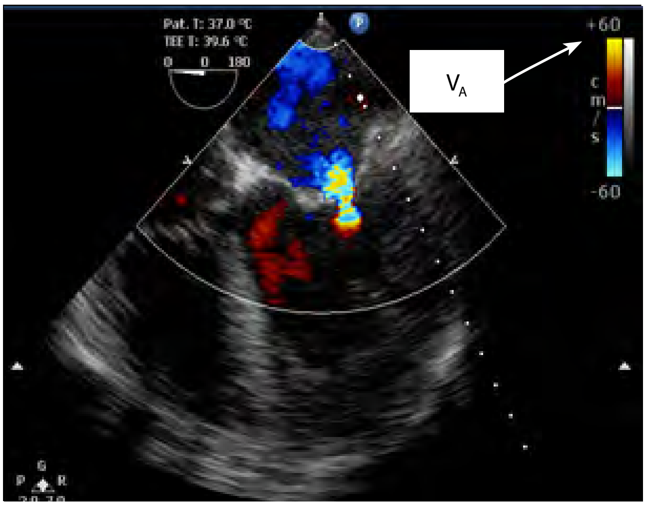

Figure 12: Aliasing velocity

Simplified proximal convergence method

This method is used by pre-emptively using the aliasing velocity (V_A) of 40 cm. With this aliasing velocity (V_A), the velocity of the regurgitant jet is assumed to be 500 cm. The simplified equation is:

EROA = (6.28 x r^2 x 40) / 500

= 0.5 x r^2

= r^2 / 2

Doppler determination of valve area

Doppler determination of valve area uses the continuity equation. The principle used is that of conservation of mass whereby flow into a chamber is equal to flow out. Figure 13 demonstrates flow (*continuous wave Doppler* red line) across a stenotic valve with depiction of changes in velocity over time with changes in cross section area.[5,6]

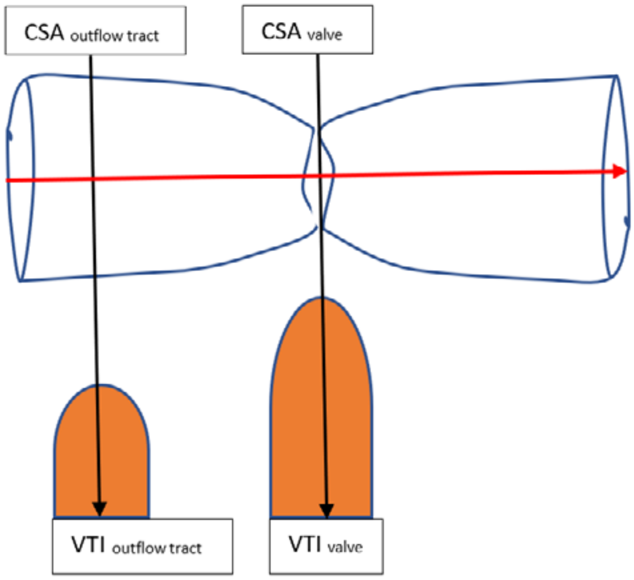

Figure 13: Continuity equation in stenotic valve

Continuity equation

FLOW IN = FLOW OUT

$SV_{VALVE} = SV_{OUTFLOW}$

CSA_{VALVE} x VTI_{VALVE} = $CSA_{OUTFLOW}$ x $VTI_{OUTFLOW}$

CSA_{VALVE} = $CSA_{OUTFLOW}$ ($VTI_{OUTFLOW}$ / VTI_{VALVE})

Continuity equation in aortic stenosis

$SV_{AV} = SV_{LVOT}$

CSA_{AV} = CSA_{LVOT} x (VTI_{LVOT} / VTI_{AV})

AVA = CSA_{LVOT} x (VTI_{LVOT} / VTI_{AV})

AVA = 0.785 x D^2_{LVOT} x (VTI_{LVOT} / VTI_{AV})

Continuity equation in mitral regurgitation (the flow convergence method)

The principle of determining the EROA using flow convergence is that flow across the mitral valve is equal to flow across the PISA. Flow is a product of area and velocity (Figure 14 and 15).[7]

$Flow_{MV} = Flow_{PISA}$

EROA x V_{REG} = PISA CSA x V_A

EROA x V_{REG} = $2\pi r^2$ x V_A

EROA = $2\pi r^2$ x V_A/V_{REG}

Continuity equation in mitral stenosis (the flow convergence method)

Similar to determination of regurgitant area using flow convergence, the mitral valve area (MVA) in mitral stenosis can be determined. The principle used is the same, however, the PISA is on the left atrial side. Due to the skewed nature of the PISA in mitral stenosis (MS), a correction factor is included in the calculation for MVA (α°/180°), where α is the angle between the stenotic mitral leaflets.

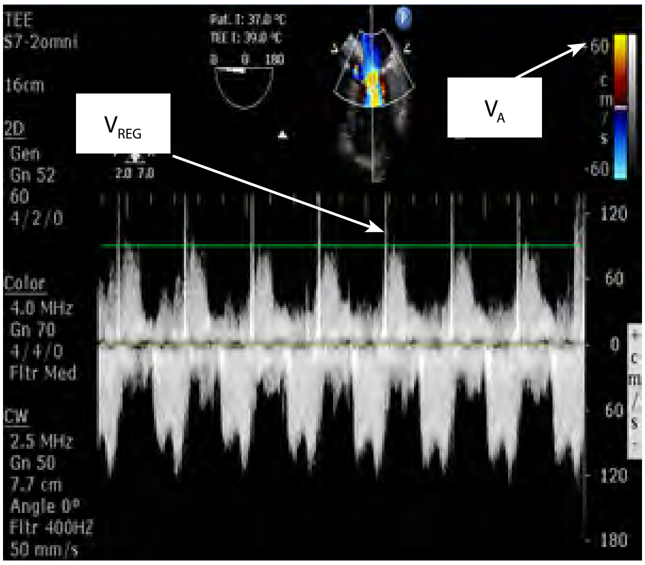

Figure 14: Peak velocity regurgitation and aliasing velocity

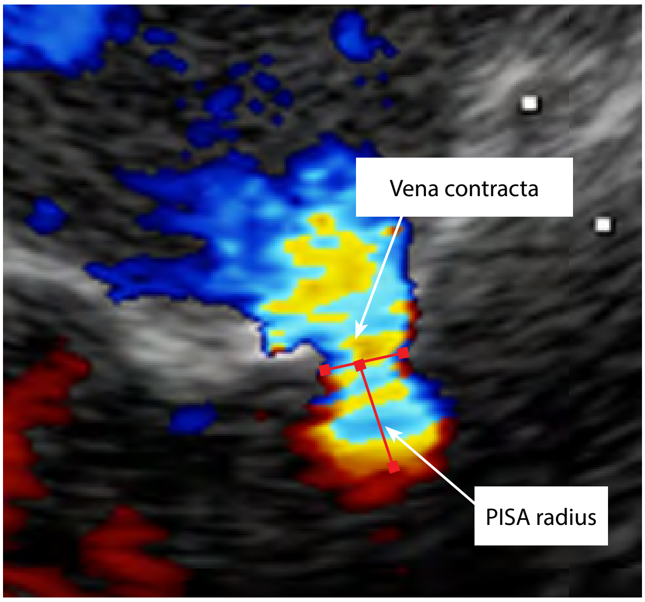

Figure 15: Vena contracta and PISA radius

$$MVA\ (cm^2) = 2\pi \times r^2 \times \text{aliasing velocity} \times (\alpha^o/180^o)$$

$$MVA\ (cm^2) = 6.28 \times r^2 \times \text{aliasing velocity} \times (\alpha^o/180^o)$$

Doppler measurement of pulmonary-to-systemic ratio

Doppler measurement of pulmonary-to-systemic flow ratio (Q_P/Q_S) is realised by using similar principles of determining SV_{LVOT} or SV_{AV} on the left side and SV_{RVOT} or SV_{PA} on the right side. The ratio is then calculated from SV on the right divided by SV on the left. It can be used to measure the magnitude of shunts.

$$(QP/QS) = SV_{PA}/SV_{LVOT}$$

$$SV\ (cm^3) = CSA\ (cm^2) \times VTI\ (cm)$$

Doppler determination of intracardiac pressures and pressure gradients

The Bernoulli equation is used to determine the pressure gradients. The relationship between the increase in velocity across an orifice and pressure gradient across orifice is determined.[8]

$$\Delta P = P2 - P1$$

$$\Delta P = ½\ \rho\ (V_2^2 - V_1^2) + \rho\ (dV/dt)\ ds + R(v)$$

where V_2 is peak velocity at stenotic valve, V_1 peak velocity proximal to stenotic valve, ρ density of the fluid (blood), ρ (dV/dt) ds flow acceleration and R(v) viscosity. In clinical echocardiography, the proximal velocity is negligible and together with the flow acceleration and viscosity, are ignored.[9] Therefore:

$$\Delta P = ½\ \rho\ V_2^2$$

An assumption is made that the density of blood to is 1.06 x 10^3 kg/m^3, therefore:

$$\Delta P = ½ \times 1.06 \times 10^3\ kg/m^3 \times V_2^2$$

$$\Delta P = 4V_2^2$$

Estimation of RVSP

$$RVSP\ (mmHg) = 4(V_{TR})^2 + RAP\ mmHg$$

$$RVSP\ (mmHg) = SBP\ mmHg - 4(V_{VSD})^2$$

[in left-right shunt]

Estimation of PASP

$$PASP\ (mmHg) = 4(V_{TR})^2 + RAP\ mmHg$$

Estimation of PADP

$$PADP\ (mmHg) = 4(V_{LATE\ PR})^2 + RAP\ mmHg$$

Estimation of MPAP

$$MPAP\ (mmHg) = 4(V_{PEAK\ PR})^2 + RAP\ mmHg$$

Estimation of LAP

$$LAP = SBP - 4(V_{MR})^2$$

Estimation of LVEDP (Figure16)

$$LVEDP\ (mmHg) = DBP\ mmHg - 4(V_{END\ AR})^2$$

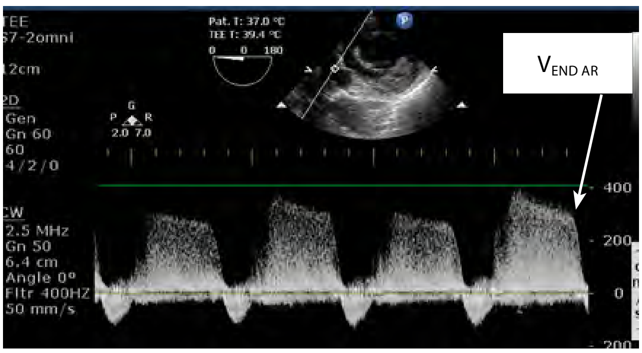

Figure 16: Late peak velocity of AR

The following book is recommended for reading: Robert M. Savage, Solomon Aronson, Stanton K. Shernan. Comprehensive Textbook of Perioperative Transesophageal Echocardiography: Edition 2. ISBN-13: 978-1605472461

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