11

Echocardiography

Virginia Luis Fuentes

Introduction

Echocardiography is probably the single most useful tool available for assessment of cardiac disease, with the possible exception of physical examination (Boon, 1998). Echocardiography is safe and versatile, giving information about both cardiac structure and function. Nevertheless, echocardiography findings should always be interpreted in the context of other clinical findings and all echocardiography results should be integrated to produce a plausible 'story'. In other words, physical examination findings, chamber enlargement and Doppler echocardiography findings should all be consistent with one another.

The echocardiographer needs to be more than just a good ultrasonographer. In addition to possessing the technical skills to record standard imaging planes in a variety of patients, the echocardiographer should have a good understanding of cardiac pathophysiology and of the haemodynamic effect of different diseases and lesions. Although a standardized protocol should form the basis of every echocardiography study, some ability to 'think on one's feet' enables additional questions to be answered during the course of the examination.

Types of echocardiography

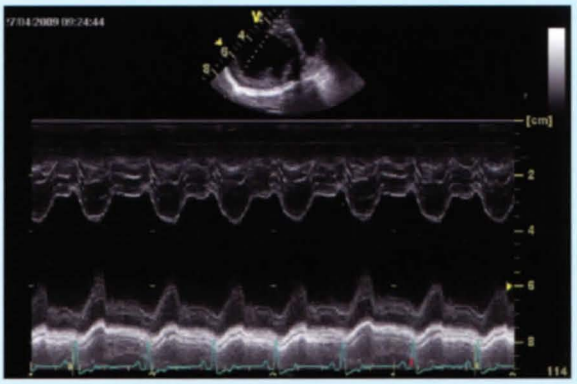
The different types of echocardiography are shown in Figure 11.1.

- *M-mode echocardiography* depicts linear dimension plotted against time.
- *Two-dimensional (2D) echocardiography* usually takes the form of a sector scan that produces tomographic slices through the heart.
- *Three-dimensional (3D) echocardiography* is also now available with some machines.
- *Doppler echocardiography* can be used to record the velocity of blood flow (*spectral Doppler*). The direction and timing of blood flow can also be depicted in colour (*colour Doppler*) superimposed on 2D black-and-white echocardiographic images. Myocardium velocity can also be recorded (*tissue Doppler imaging, TDI*).

M-mode echocardiography

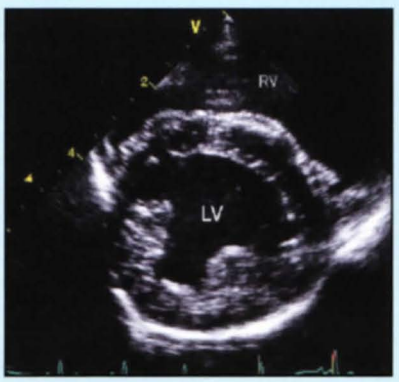
M-mode echocardiography is limited to providing information in one plane only. The cursor is aligned using a 2D image, and the action of the anatomical structures of the heart crossed by the cursor are plotted against time. The advantage of M-mode echocardiography is the excellent time resolution for measurement of cardiac dimensions at precise time points. The main disadvantage is that the sampling area is very limited. M-mode echocardiography gives little information about changes in cardiac size or shape in other dimensions, or about specific lesions. It is also quite technically demanding, which is often under-appreciated. M-mode echocardiography remains widely used for measuring left ventricular diameters.

M-mode



A linear point-source of ultrasound waves is oriented using the 2D image (see cursor in small image) to produce a graph of depth against time

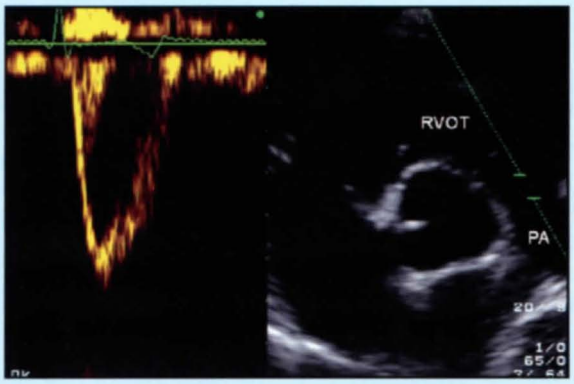
2D



A wedge-shaped sector of ultrasound waves is used to produce a tomographic image of the heart
LV = Left ventricle; RV = Right ventricle

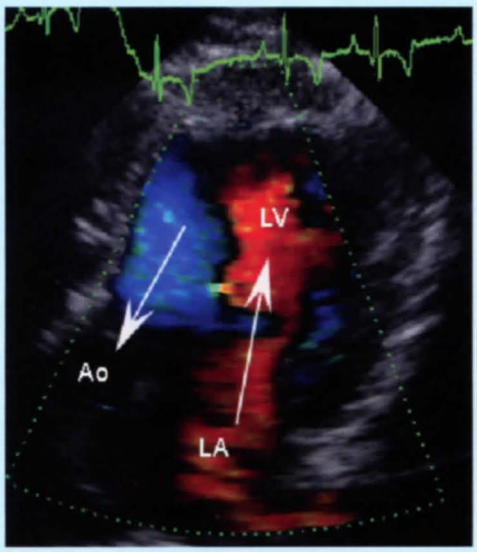
11.1 Types of echocardiography. (continues) ▶

Spectral Doppler



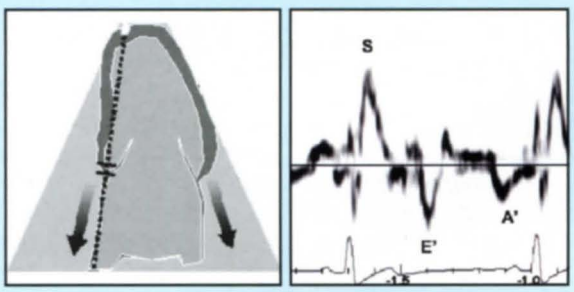
Velocity–time graph of blood flow
The cursor is aligned on the 2D image, parallel with flow
Blood flow velocity is recorded within the 'region of interest' (pulsed wave, PW) or along the length of the cursor (continuous wave, CW)
PA = Pulmonary artery; RVOT = Right ventricular outflow tract

Colour flow Doppler



Blood flow is 'coded' in colour and superimposed on a 2D image. Red shows blood flow towards the transducer. Blue shows blood flow away from the transducer
Ao = Aorta; LA = Left atrium; LV = Left ventricle

Tissue Doppler imaging (TDI)



Velocity–time graph of myocardial motion
The cursor is aligned parallel to myocardial motion, and velocities are recorded within a 'region of interest' (PW-TDI)
A' = Atrial TDI mitral annular velocity; E' = Early diastolic TDI mitral annular velocity; S = Systolic TDI mitral annular velocity

11.1 (continued) Types of echocardiography.

2D echocardiography

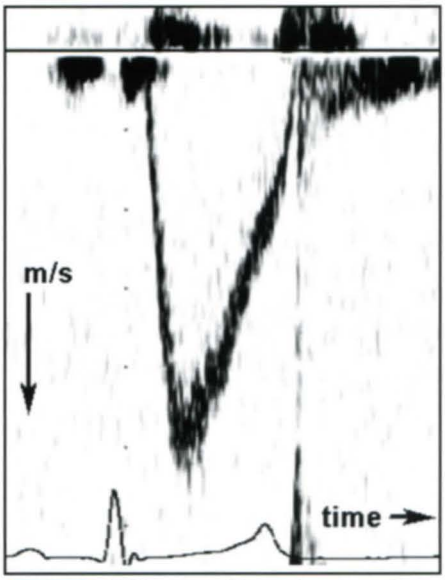
2D echocardiography is very versatile, as many different slices can be made through the heart to provide numerous different imaging planes. In this way, 2D echocardiography can demonstrate abnormalities of cardiac size and shape, as well as lesions. 2D frame rates are now sufficiently good on many machines that there is little advantage to using M-mode echocardiography, and many quantitative measurements are made directly from 2D images (see Figures 11.8, 11.9 and 11.11). More importantly, there is much qualitative information available in 2D echocardiography.

Doppler echocardiography

Doppler echocardiography gives information about the *direction* and *velocity* of blood flow, utilizing the Doppler principle whereby the frequency of reflected ultrasound waves is changed if the reflecting target is moving towards or away from the source. It is critically angle-dependent: the beam of ultrasound waves *must* be parallel with the direction of the moving target (i.e. blood flow).

Spectral Doppler

With spectral Doppler, the velocity is displayed as a velocity–time graph (Figure 11.2), with blood flow away from the transducer displayed below the baseline and blood flow towards the transducer displayed above the baseline.



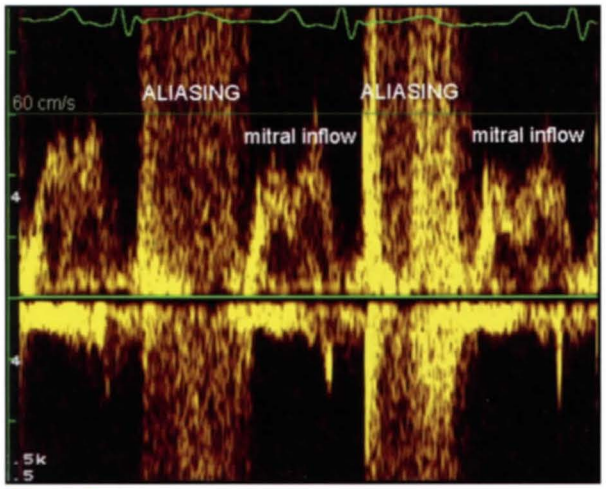
11.2 PW spectral Doppler recording of aortic blood flow. Velocity (m/s) is displayed along the y axis and time is displayed along the x axis. An ECG is shown for reference.

For all forms of spectral Doppler, the most important consideration is to *align the cursor parallel with flow*, or peak velocity will be underestimated. Spectral Doppler varies according to the sampling area:

- In *pulsed wave (PW) Doppler echocardiography*, a very limited area of blood flow is sampled. A user-defined 'region of interest' (or 'sample volume') samples velocities in a specific site, using a 2D image for guidance. This allows

precise localization of blood flow velocities, but this restricts the maximum velocity that can be displayed unambiguously. High velocity flow cannot be recorded accurately, as it results in '*aliasing*', where the velocity 'wraps around the baseline' (Figure 11.3)

- In *continuous wave (CW) Doppler echocardiography*, blood flow is sampled along the entire length of the cursor. This allows much higher velocities to be displayed, but there is 'range ambiguity' as the exact location of the high velocity flow along the cursor cannot be determined from the spectral signal.



11.3 PW spectral Doppler recording of mitral valve inflow (above the baseline during diastole) with an aliased signal during systole caused by high velocity mitral regurgitation.

The velocity of blood flow primarily depends on the driving pressure (pressure gradient), and can be estimated using the simplified Bernoulli equation:

$$\text{Pressure gradient (mmHg)} = 4 \times \text{velocity}^2$$

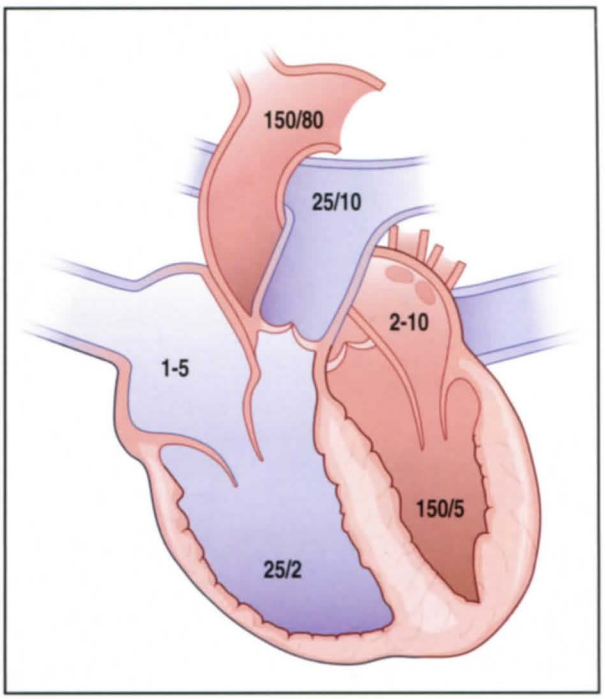
This equation allows estimation of pressure gradients (not absolute pressures) and so knowledge of normal intracardiac pressures is necessary (Figure 11.4).

Colour Doppler

Colour Doppler can resolve some of the problems of range ambiguity found with CW Doppler, as high velocity or turbulent flow can be displayed as a different colour superimposed on the 2D black-and-white image. Flow towards the transducer is coded as red, and flow away from the transducer is coded as blue. *Aliasing will still occur with high velocities* and is displayed as reversal of colour (red to blue, or blue to red). *Variance* occurs with turbulent flow (usually displayed as green).

Technique

Most dogs can be scanned without sedation, but handling must be particularly sensitive when scanning non-sedated cats. Sedation with an opiate such as butorphanol is often sufficient to improve patient cooperation. Clipping of the haircoat improves contact between the probe and the skin, but is not always essential. Sufficient use of acoustic gel is vital for good image quality.



11.4 Normal approximate pressures (mmHg) in the cardiac chambers and great vessels. Right-sided heart chambers are blue, left-sided heart chambers are red.

Most echocardiographers scan small animal patients in lateral recumbency, using a table with a cut-out area to enable scanning from underneath. It is also possible to scan the patient in a standing position. A simultaneous *electrocardiogram (ECG)* allows accurate timing of events within the cardiac cycle and concurrent screening for arrhythmias, and facilitates acquisition of digital image loops.

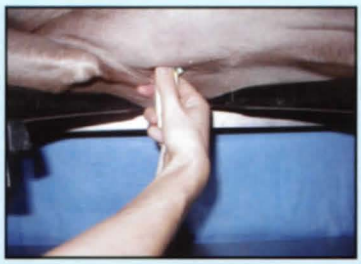
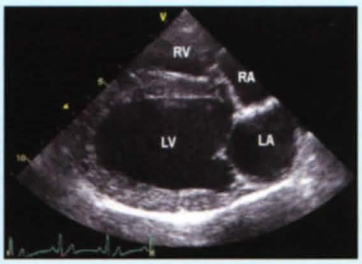
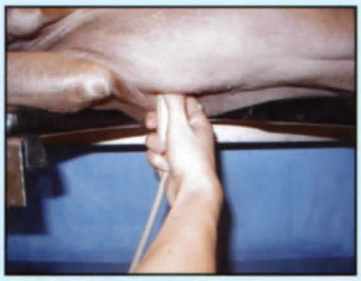
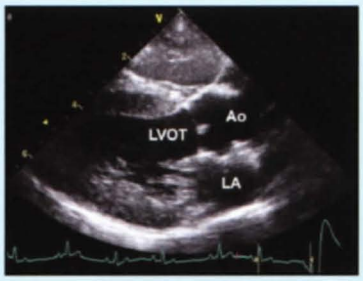
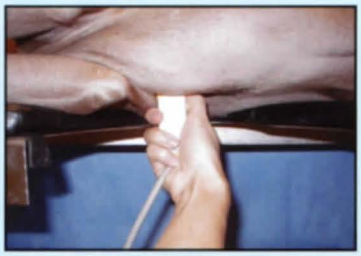
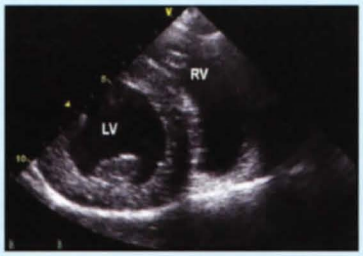
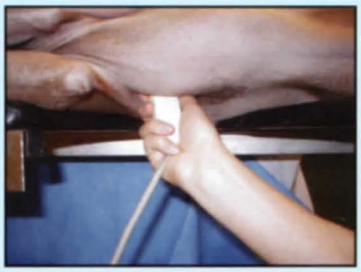
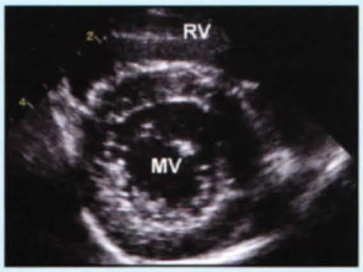
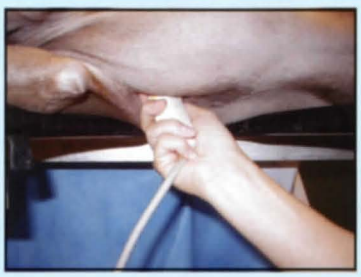
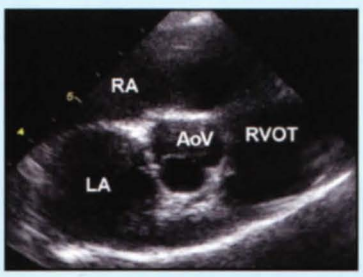
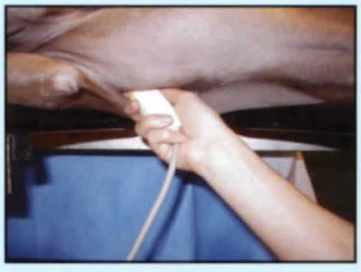
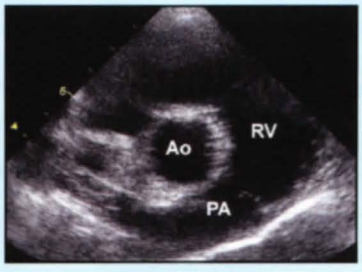
A standard protocol should be adopted so that a set sequence of views is recorded. Some views are more difficult than others and it may not be possible to obtain all views in all patients. Sometimes additional non-standard views may be needed, as it is important that any abnormalities are followed up during the study, acquiring additional views or velocity flow patterns as needed.

2D views

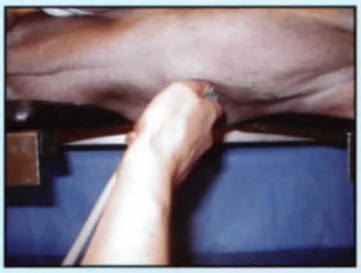
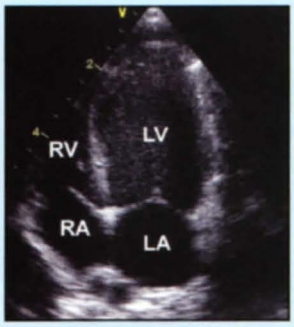
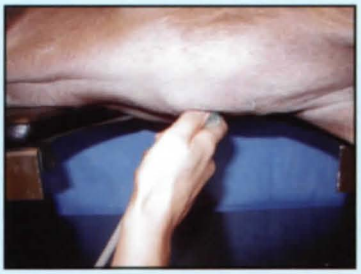
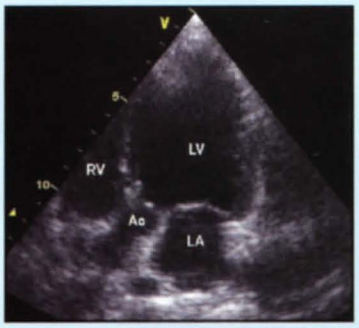
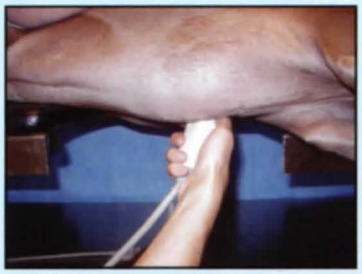
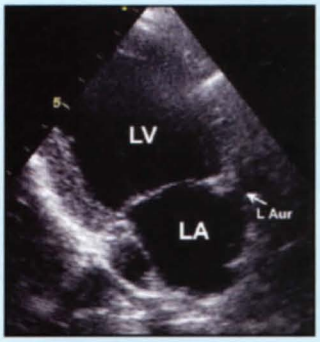
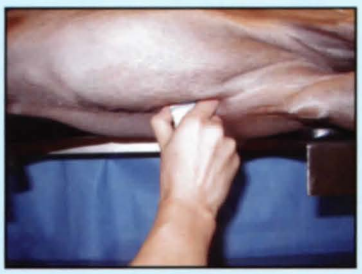
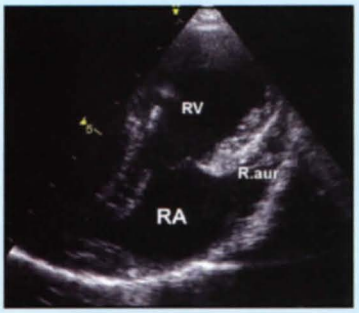
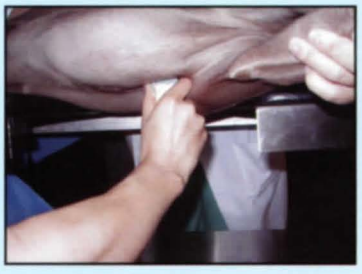
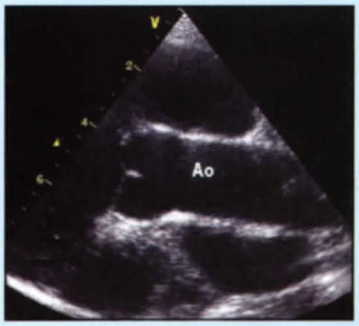
The standard right-sided views are shown in Figure 11.5 and the standard left-sided views are shown in Figure 11.6, together with common applications of each view.

Doppler views

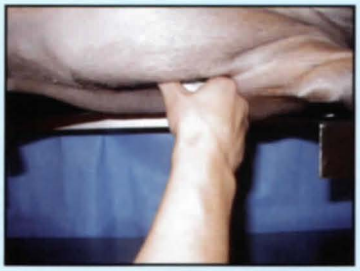
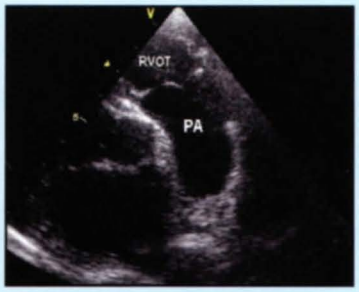
Flow through each valve should be interrogated at multiple locations for the best alignment (Figure 11.7). *Fast or turbulent blood flow* is always of interest, as it usually results in a murmur and may occur as a result of valvular regurgitation, valvular stenosis or a shunt.

View	Probe position	Image	Uses
Right parasternal long-axis four chamber			2D: Excellent overview of all four chambers LA dimensions LV dimensions Mitral valve morphology and motion Colour Doppler: Mitral regurgitation Tricuspid regurgitation
Right parasternal long-axis five chamber			2D: LVOT abnormalities LV wall thickness Ventricular septal defects Systolic anterior motion of the mitral valve Colour Doppler: LVOT obstruction Aortic regurgitation Mitral regurgitation
Right parasternal short-axis (papillary muscle level)			2D: LV dimensions Relationship between LV and RV pressures M-mode: LV dimensions
Right parasternal short-axis (mitral valve level)			2D: Mitral valve morphology M-mode: E-point to septal separation Colour Doppler: Mitral regurgitation
Right parasternal short-axis (aortic valve level)			2D: LA dimensions Aortic valve morphology Interatrial septum abnormalities 2D/Colour Doppler: Ventricular septal defects Tricuspid valve abnormalities
Right parasternal short-axis (pulmonary artery level)			2D: RVOT/pulmonic valve morphology Colour Doppler: Tricuspid regurgitation Pulmonary artery blood flow Patent ductus arteriosus Spectral Doppler: Pulmonary artery blood flow velocities

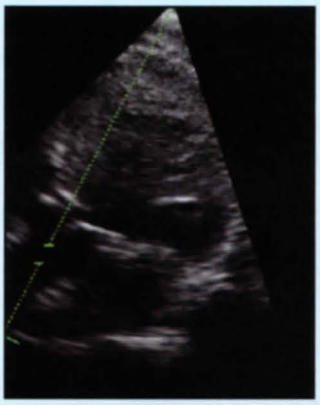
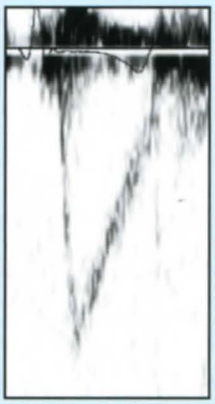
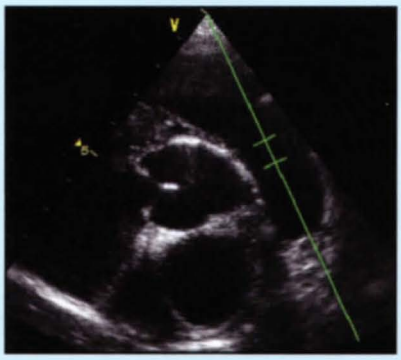
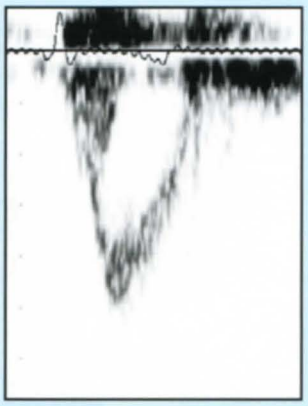
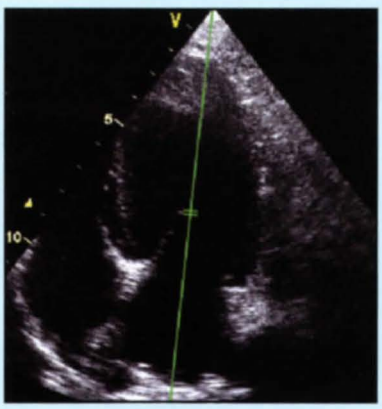
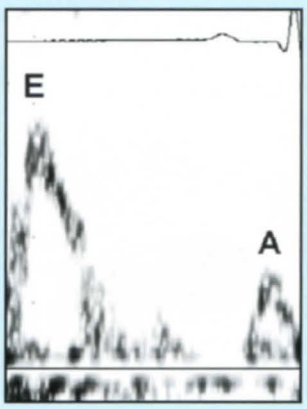
11.5 Standard right-sided echocardiographic views. Ao = Aorta; AoV = Aortic valve; LA = Left atrium; LV = Left ventricle; LVOT = Left ventricular outflow tract; MV = Mitral valve; PA = Pulmonary artery; RA = Right atrium; RV = Right ventricle; RVOT = Right ventricular outflow tract.

View	Probe position	Image	Uses
Left apical four chamber			2D: Overview of all four chambers Mitral valve morphology and function Colour Doppler: Mitral regurgitation Tricuspid regurgitation Spectral Doppler: Mitral valve inflow
Left apical five chamber			2D: LVOT Colour Doppler: LVOT obstruction Aortic regurgitation Spectral Doppler: Aortic flow velocity
Left apical two chamber			2D: LAur Colour Doppler: Mitral regurgitation Spectral Doppler: Mitral valve inflow
Left cranial tricuspid valve			2D: Tricuspid valve morphology and function RAur Colour Doppler: Tricuspid regurgitation Spectral Doppler: Tricuspid inflow Tricuspid regurgitation
Left cranial aorta			2D: Aortic valve morphology Ascending aorta Colour Doppler: Aortic regurgitation

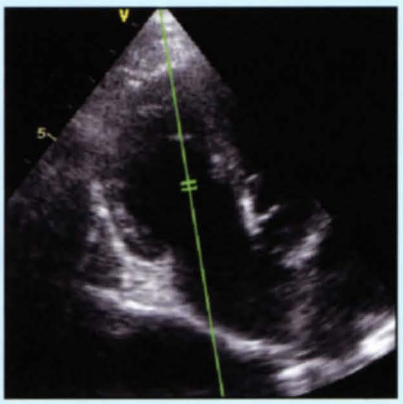
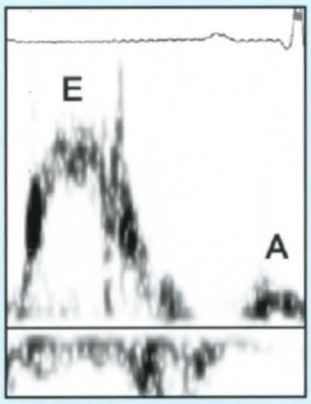
11.6 Standard left-sided echocardiographic views. Ao = Aorta; LA = Left atrium; LAur = Left auricular appendage; LV = Left ventricle; LVOT = Left ventricular outflow tract; RA = Right atrium; RAur = Right auricular appendage; RV = Right ventricle. (continues) ▶

View	Probe position	Image	Uses
Left cranial pulmonary artery			2D: Pulmonic valve morphology Colour Doppler: Pulmonary artery blood flow Patent ductus arteriosus flow

11.6 (continued) Standard left-sided echocardiographic views. PA = Pulmonary artery; RVOT = Right ventricular outflow tract.

View	Cursor placement	PW spectral Doppler image	Normal velocities
Subcostal (or left apical five chamber) showing aortic valve velocity			Peak velocity: <1.7 m/s left apical <2.0 m/s subcostal
Left cranial (or right parasternal) showing pulmonary artery velocity			Peak velocity: <1.5 m/s
Left apical four chamber (or two chamber) showing mitral valve velocity			Peak velocity: E: 0.5–1.0 m/s A: 0.3–0.6 m/s

11.7 Normal PW spectral Doppler echocardiographic views. (continues) ▶

View	Cursor placement	PW spectral Doppler image	Normal velocities
Left apical four chamber (or left cranial) showing tricuspid valve velocity			Peak velocity: E: 0.3–0.9 m/s A: 0.3–0.6 m/s

11.7 (continued) Normal PW spectral Doppler echocardiographic views.

Chamber measurements

Echocardiography is ideally suited to identification of structural lesions, but quantitative assessment of cardiac dimensions and function is also important. Estimates of chamber dimensions should always be interpreted in the context of qualitative information.

Measurements are most important when assessing left heart dimensions, partly because the left heart is an easier shape to quantify than the right, and partly because the most important acquired diseases primarily affect the left heart. As a general rule, measurements should be taken from at least three cardiac cycles and averaged.

Left atrium

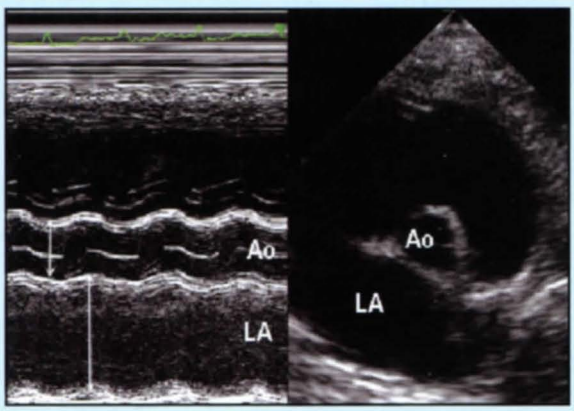
Quantification of left atrium (LA) size is an extremely important application of cardiac imaging, as it strongly relates to risk of pulmonary oedema and clinical signs. Although M-mode echocardiography is still sometimes used for measurement of LA size (particularly in cats), it has largely been superseded by 2D techniques (Hansson *et al.*, 2002). A summary of methods for LA size evaluation is given in Figure 11.8.

Left ventricle

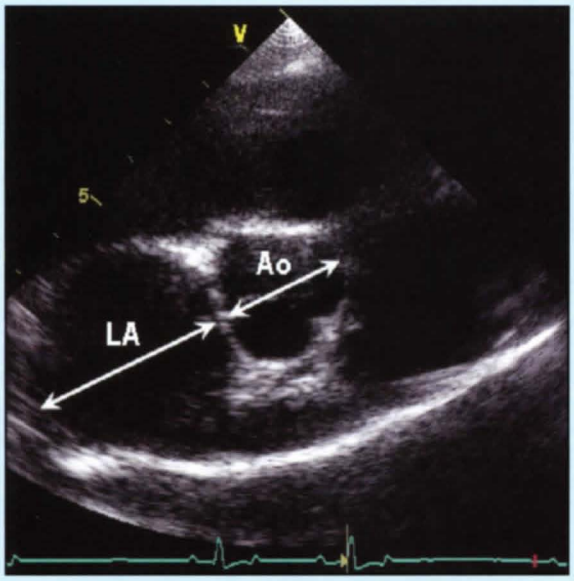
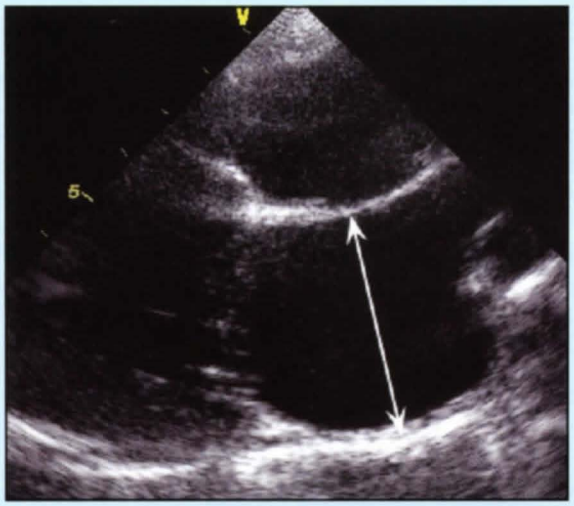
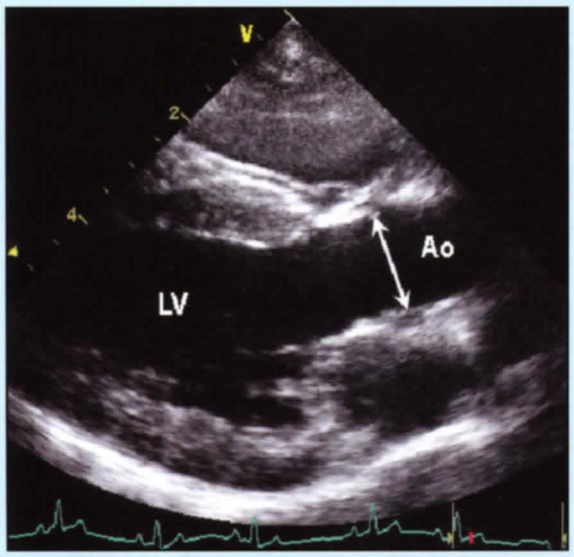
Methods of assessing left ventricle (LV) size are listed in Figure 11.9.

Diameter: M-mode echocardiography is still the most commonly used method for quantifying LV diameter. There are inherent pitfalls with M-mode, as it can be difficult to recognize oblique or off-centre views. The diameter measured differs according to whether a short-axis or long-axis 2D view has been used to acquire the M-mode (Schober and Baade, 2000). *M-mode should not be used to derive LV volumes.* Normal canine reference intervals are problematic because of the range in bodyweight and conformation. Methods used to compensate for the range of sizes include:

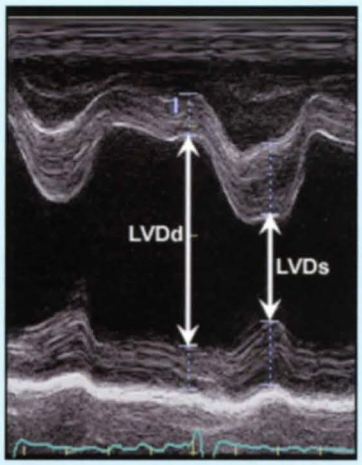
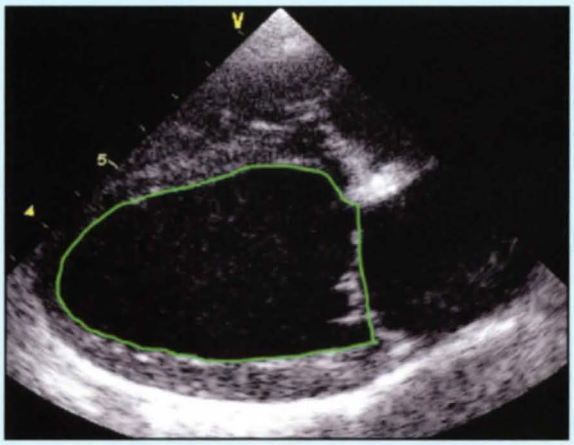
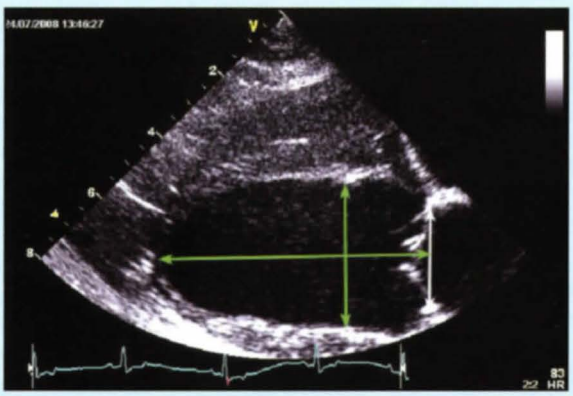
- Ratio indices
- 'Cornell' method
- Breed-specific values.

Image	Technique	Normal values
M-mode (LA:Ao$_{M\text{-}mode}$)		
	Timing: Aorta measured at the start of the QRS complex LA measured at end-systole Measure: Leading edge to leading edge	LA:Ao$_{M\text{-}mode}$ Dogs and cats: <1.3

11.8 Measurement of LA dimensions. Ao = Aorta; LA = Left atrium. (continues) ▶

Image	Technique	Normal values
Short axis ($LA:Ao_{SAX}$)		
	Timing: Early diastole (when the aortic valve leaflets are closed) Measure: Aorta from middle of right coronary cusp to commissures between the left and non-coronary cusps LA from line extending from aortic measurement out to wall of LA, trying to avoid the pulmonary vein Inside edge to inside edge	$LA:Ao_{SAX}$ Dogs: <1.6 Cats: <1.5
Long axis (LA_{LAX} and Ao_{LAX})		
	Timing: End-systole Measure: LA from the interatrial septum to the epicardial surface of the LA free wall, bisecting the LA Inside edge to inside edge	LA_{LAX} Cats: <1.6 cm
	Timing: Systole Measure: Between the open aortic leaflets Inside edge to inside edge	$LA_{LAX}:Ao_{LAX}$ Dogs: <2.5

11.8 (continued) Measurement of LA dimensions. Ao = Aorta; LA = Left atrium; LV = Left ventricle.

View	Image	Technique	Normal values
M-mode LV diameter		Timing: End-diastole: at start of the QRS complex (this is not necessarily maximum LV diameter) End-systole: at peak septal motion (this is not necessarily the same time as peak free wall motion) Leading edge to leading edge	Dogs: Varies with size and breed Consider Cornell method (see Figure 11.10) Cats: LVDd: 11–20 mm LVDs: 6–15 mm
2D LV volumes		Timing: End-diastole: at first frame after the mitral valve closes before systole End-systole: at smallest LV dimensions before the mitral valve opens Trace endocardial border from septal mitral valve annulus to lateral wall mitral valve annulus **Vital to obtain true apex**	Dogs: Varies with size and breed Normal reference intervals not established
Sphericity index		Timing: End-diastole Length: measured from line across mitral valve annulus to apex Diameter: taken at chordal level or from M-mode LVDd	Dogs: Length/diameter: ≥1.7 (may be higher in narrow-chested dogs)

11.9 Measurement of LV dimensions. LV = Left ventricle; LVDd = Left ventricular diameter in diastole; LVDs = Left ventricular diameter in systole.

Ratio indices: These can be used for LV diameters just as they can for the LA (Brown *et al.*, 2003). In some ways this technique mimics subjective assessment of LV diameters, as experienced observers often 'eyeball' changes in chamber dimensions by noting differences in size relative to other chambers or vessels. The ratio of the LV diameter to the actual (or predicted) aortic diameter is relatively consistent.

Cornell method: The Cornell method uses a similar calculation, acknowledging that the relationship between bodyweight and LV diameter is not linear (Cornell *et al.*, 2004). LV diameters are predicted based on normalizing the diameter to approximately the cube root of the bodyweight (Figure 11.10):

- Predicted LVDd = LVDd × 1.53 × $BW^{0.294}$
- Predicted LVDs = LVDs × 0.95 × $BW^{0.315}$

Where: BW = Bodyweight; LVDd = Left ventricular diameter in diastole; and LVDs = Left ventricular diameter in systole.

Bodyweight (kg)	LVDd (cm)	LVDs (cm)	LVFWd (cm)	IVSd (cm)
3	2.1 (1.8–2.6)	1.3 (1.0–1.8)	0.5 (0.4–0.8)	0.5 (0.4–0.8)
4	2.3 (1.9–2.8)	1.5 (1.1–1.9)	0.6 (0.4–0.8)	0.6 (0.4–0.8)
6	2.6 (2.2–3.1)	1.7 (1.2–2.2)	0.6 (0.4–0.9)	0.6 (0.4–0.9)
9	2.9 (2.4–3.4)	1.9 (1.4–2.5)	0.7 (0.5–1.0)	0.7 (0.5–1.0)
11	3.1 (2.6–3.7)	2.0 (1.5–2.7)	0.7 (0.5–1.0)	0.7 (0.5–1.1)
15	3.4 (2.8–4.1)	2.2 (1.7–3.0)	0.8 (0.5–1.1)	0.8 (0.6–1.1)
20	3.7 (3.1–4.5)	2.4 (1.8–3.2)	0.8 (0.6–1.2)	0.8 (0.6–1.2)
25	3.9 (3.3–4.8)	2.6 (2.0–3.5)	0.9 (0.6–1.3)	0.9 (0.6–1.3)
30	4.2 (3.5–5.0)	2.8 (2.1–3.7)	0.9 (0.6–1.3)	0.9 (0.7–1.3)
35	4.4 (3.6–5.3)	2.9 (2.2–3.9)	1.0 (0.7–1.4)	1.0 (0.7–1.4)
40	4.5 (3.8–5.5)	3.0 (2.3–4.0)	1.0 (0.7–1.4)	1.0 (0.7–1.4)
50	4.8 (4.0–5.8)	3.3 (2.4–4.3)	1.0 (0.7–1.5)	1.1 (0.7–1.5)
60	5.1 (4.2–6.2)	3.5 (2.6–4.6)	1.1 (0.7–1.6)	1.1 (0.8–1.6)
70	5.3 (4.4–6.5)	3.6 (2.7–4.8)	1.1 (0.8–1.6)	1.1 (0.8–1.6)

11.10 Predicting canine LV M-mode measurements based on allometric scaling. (Data from Cornell *et al.*, 2004).

Breed-specific values: These are the ideal source for reference intervals and are preferred when available.

Volumes: 2D echocardiography can be used to record LV volumes, which should *not* be calculated using M-mode measurements. The right parasternal view is normally used, but great care must be taken to include the true apex of the LV (this requires practice). The endocardial borders of the LV are traced, ignoring the papillary muscles and drawing a straight line across the mitral valve annulus. The LV volume is calculated using either a modified Simpson's technique (method of discs) or an area–length formula.

The normal LV end-systolic volume (ESV) and end-diastolic volume (EDV) will vary according to size and breed. The LV volumes can be normalized by dividing by body surface area to produce an end-diastolic volume index (EDVI) or an end-systolic volume index (ESVI).

Sphericity index: Rather than measuring absolute diameter, an alternative way to identify increased LV dimensions is to look for a change in LV geometry, or LV 'remodelling'. This can be done by noting an increase in LV diameter in relation to LV length. The LV long axis/short axis ratio is called the sphericity index, and reduced values indicate a more spherical LV. Short axis dimensions can be obtained by M-mode echocardiography, and long axis dimensions from 2D views. Diastolic dimensions are normally used. Ideally, normal values for each breed should be derived. Deep-chested dogs have more elongated hearts, and the normal sphericity index may be greater than the figure of ≥1.7 in general use.

Left ventricular wall thickness

Cats: Measurement of LV wall thickness is much more important in cats than in dogs (Figure 11.11). The criteria used to determine LV hypertrophy vary, but whichever technique is used it is *crucial to measure the end-diastolic frame*, as measurement at any other time point will result in over-estimation of wall thickness. It is also important to avoid including extraneous echoes from LV 'false tendons'.

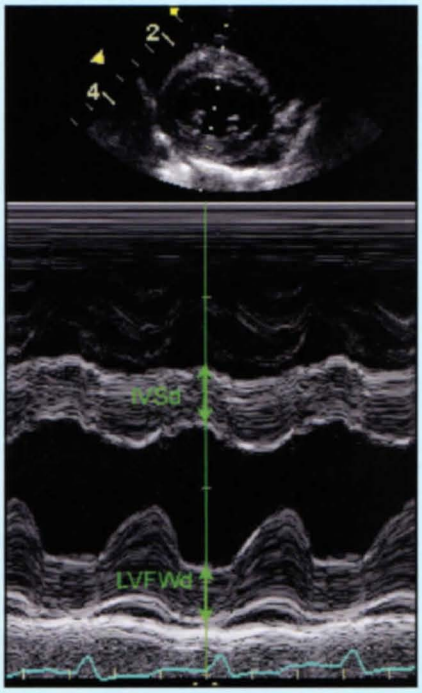
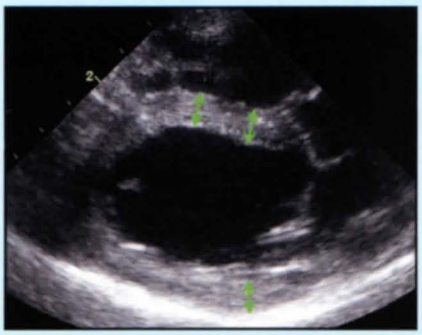
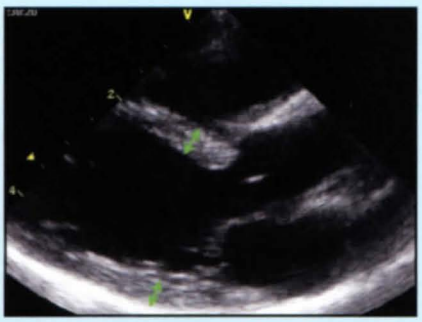
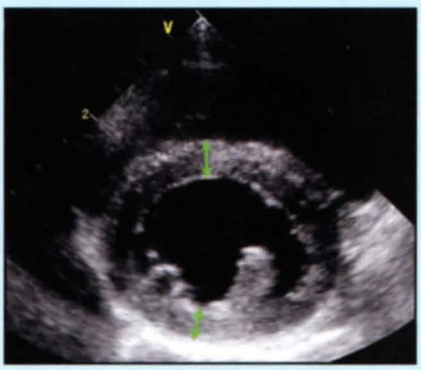
M-mode measurement is restricted to one area of the septum and free wall. This means that regions of LV hypertrophy in other areas may be missed. Therefore, many practitioners use a cut-off value of <5.5 mm as normal, reflecting the decreased sensitivity of M-mode echocardiography for detection of LV hypertrophy. It is also difficult to avoid papillary muscles, which can lead to falsely increased free wall measurements.

2D echocardiography allows measurement of hypertrophy in other areas. The maximal wall thickness is measured in up to three views. It is easier to avoid including false tendons and papillary muscles using 2D images (Figure 11.12).

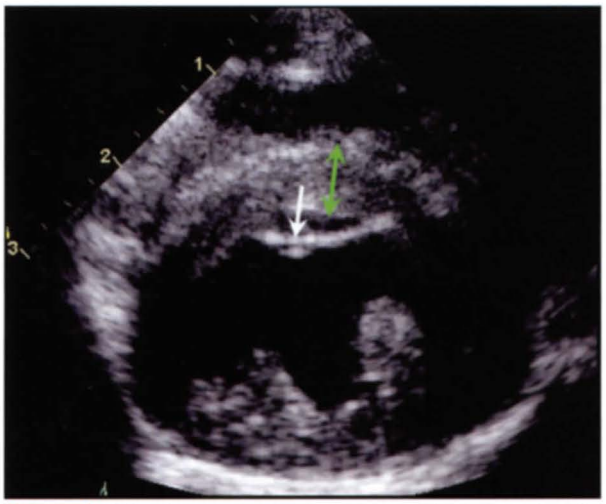
Dogs: There are fewer indications for measuring wall thickness in dogs, although aortic stenosis and systemic hypertension may result in LV hypertrophy. The Cornell method is probably the best method for identifying hypertrophy:

- Predicted IVSd = IVSd × 0.41 × $BW^{0.241}$
- Predicted LVFWd = LVFWd × 0.42 × $BW^{0.232}$

Where: BW = Bodyweight; IVSd = Interventricular septal thickness in diastole; and LVFWd = Left ventricular free wall thickness in diastole (see Figure 11.10).

View	Image	Technique	Normal values
M-mode LV wall thickness		Timing: End-diastole: at start of QRS complex Leading edge to leading edge	Cats: IVSd, LVFWd: ≤5.5 mm Dogs: Varies with size and breed Consider Cornell method
2D LV wall thickness	  	Timing: End-diastole: wall thickness at first frame after mitral valve closes before systole Measure in right parasternal long-axis four chamber view, right parasternal long-axis five chamber view and short-axis view (see Figure 11.5). **Avoid papillary muscles and false tendons**	Cats: Maximal diastolic thickness: <6 mm in any view

11.11 Measurement of left ventricular wall thickness. IVSd = Interventricular septal thickness in diastole; LV = Left ventricle; LVFWd = Left ventricular free wall thickness in diastole.



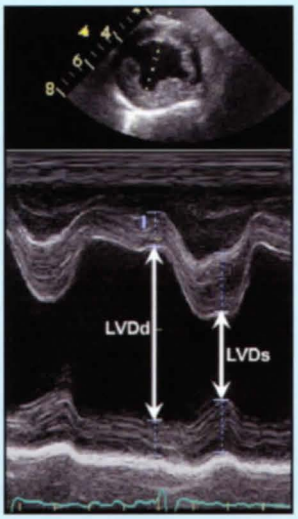
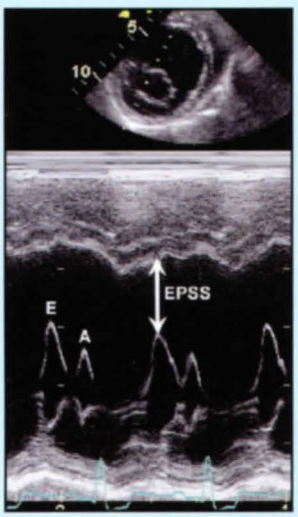
11.12 2D right parasternal short-axis view at the level of the papillary muscle in a cat. The interventricular septal thickness is shown by the green arrow. The white arrow indicates a false tendon, which can easily be mistaken for the endocardial surface of the LV (falsely increasing wall thickness).

Systolic function

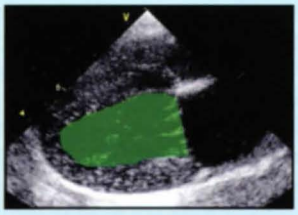
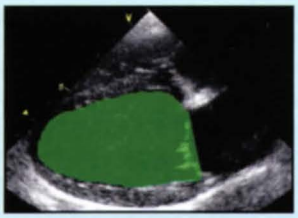
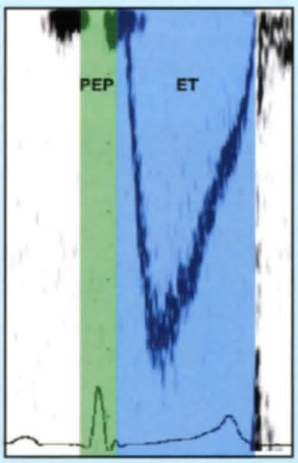
Measurement of systolic function is particularly important for diagnosis of dilated cardiomyopathy (DCM), but systolic function may also be abnormal in other conditions. Most echocardiographic methods of measuring systolic function (Figure 11.13) are profoundly affected by loading conditions. *LV wall motion is increased with increased preload and decreased afterload.* This is particularly important with mitral regurgitation, where the effects of the regurgitation itself on preload and afterload result in a hyperdynamic LV, thus potentially masking any underlying systolic dysfunction. Particular care should be taken in the setting of moderate to severe mitral regurgitation when echocardiography measurements of systolic function are in the low normal range, as this is likely to indicate reduced systolic function.

Fractional shortening

The percentage change in LV diameter in systole is called the LV fractional shortening (FS). This is usually

View	Image	Technique	Normal values
M-mode fractional shortening (FS%)		Timing: LVDd: measured at end-diastole at the start of the QRS complex LVDs: measured at peak septal motion Leading edge to leading edge FS% = (LVDd – LVDs)/LVDd x 100	Dogs: 25–50% Cats: 30–50%
M-mode E-point to septal separation (EPSS)		Timing: Peak opening of mitral valve in early systole From leading edge of septal LV endocardial surface to leading edge of anterior mitral valve leaflet	Dogs: <7 mm in large dogs

11.13 Measurement of left ventricular systolic function. LV = Left ventricle; LVDd = Left ventricular diameter in diastole; LVDs = Left ventricular diameter in systole. (continues) ▶

View	Image	Technique	Normal values
LV end-systolic volume index (ESVI)		Timing: End-systolic volume (ESV) at smallest LV dimensions before mitral valve opens Trace endocardial border from septal mitral valve annulus to lateral wall mitral valve annulus **Vital to obtain true apex**	ESVI: ESV/body surface area ≤30 ml/m^2
2D ejection fraction (EF%)		Timing: End-diastolic volume (EDV) at first frame after mitral valve closes before systole ESV at smallest LV dimensions before mitral valve opens EF% = (EDV – ESV)/EDV x 100	Dogs: 50–65%
LV systolic time intervals		Aortic spectral Doppler Timing: Pre-ejection period (PEP): from start of QRS complex to onset of aortic ejection (green) Ejection time (ET): duration of aortic spectral Doppler flow signal (blue)	Dogs: PEP/ET: 0.24–0.38

11.13 (continued) Measurement of left ventricular systolic function. LV = Left ventricle.

measured from an M-mode image obtained from a short-axis view. FS is the most commonly used measurement of systolic function, but should not be used as the sole measurement if values are below the normal reference intervals. Other indicators of systolic function should always be measured in addition to FS before diagnosing systolic dysfunction (see Chapter 23). LV dilatation also increases suspicion that systolic dysfunction is genuine (Dukes-McEwan *et al.*, 2003).

Mitral E-point to septal separation

M-mode images can also be used to measure the maximal opening of the mitral valve in diastole, by measuring the distance between the septum and early opening (E-point) of the anterior mitral valve leaflet (EPSS). This distance is increased with systolic dysfunction, but care should be taken to avoid oblique views. EPSS is used far less than FS.

Left ventricle end-systolic volume index

The end-systolic volume (ESV) can be normalized to body surface area. Although normal values of 30 ml/m^2 are often quoted, it should be noted that this may not be valid for smaller breeds of dog.

2D left ventricle ejection fraction

The percentage change in LV volume during systole can be calculated from the volumes measured from a right parasternal long-axis view. Generally, LV wall definition in left apical views is less good, and the maximal length of the LV can be more easily derived from right-sided views. *Ejection fraction* (EF) *should not be derived from volumes estimated from M-mode measurements*. When calculated from 2D images, EF more accurately assesses global systolic function (rather than systolic function at one level and in one plane as with M-mode images).

Systolic time intervals

A different method of assessing systolic function uses the timing of ejection with respect to electrical activation. The interval between the beginning of the Q wave on the ECG and the onset of ejection of blood into the aorta (the *pre-ejection period,* PEP) can be divided by the duration of aortic ejection (the *ejection time,* ET) to give the systolic time interval PEP/ET. This ratio is increased with systolic dysfunction and can be measured from the spectral Doppler flow signal with a concurrent ECG. As with other echocardiographic indices of systolic function, PEP/ET should be interpreted in

the light of concurrent cardiac abnormalities, since systolic time intervals can still be affecting by loading conditions or heart rate (Boon, 1998).

Valve function

Echocardiography allows assessment of valve function in a number of different ways:

- Valve lesions can be assessed with 2D imaging
- Chamber remodelling can be assessed by 2D and M-mode imaging
- Disturbed blood flow can be assessed by colour and spectral Doppler imaging
- Pressure gradients, flow rates and orifice area can be calculated with a combination of spectral Doppler, colour Doppler and 2D imaging.

Methods used to assess valvular stenosis may differ slightly from those used for valvular insufficiency, but a combination of methods is always more reliable than a single method.

Valvular regurgitation

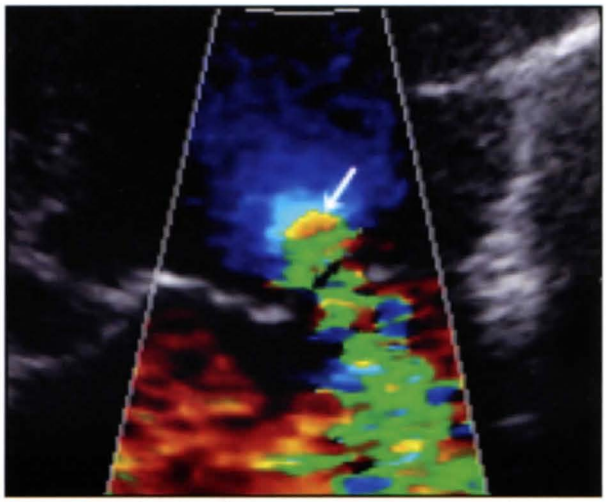
Mitral regurgitation

Valve lesions: 2D echocardiography can provide an enormous amount of information on structural abnormalities of the mitral valve, abnormal motion and secondary effects on chamber remodelling. DCM can also cause severe mitral regurgitation, so it is important to assess mitral valve morphology. In myxomatous mitral valve disease (MMVD) the mitral valve leaflets may prolapse, with thickening and distortion developing as structural changes become more severe. In very severe cases, a flail segment may indicate a previously ruptured chord. In DCM, valve leaflets will not be thickened, and may be 'tethered' rather than prolapsed. A summary of methods used for grading mitral regurgitation is given in Figure 11.14.

Chamber remodelling: LA and LV diameter will be increased with severe mitral regurgitation, although this is unreliable in acute regurgitation.

Disturbed flow: Colour flow Doppler can be used to identify jets of mitral regurgitation. A semi-quantitative estimate of mitral regurgitation severity can be made by relating the *jet area* to the LA area, as mild mitral regurgitation produces a small narrow jet. Large jets filling the LA are likely to indicate severe mitral regurgitation. Care should be taken with eccentric jets, where the jet area will be less than expected for the severity of the mitral regurgitation. It should be noted that *jet area is strongly influenced by colour gain controls.*

With a large regurgitant orifice (i.e. a large opening in the closed mitral valve), a large volume of blood will flow backwards from the LV to the LA. The blood accelerates as it passes through the regurgitant orifice, aliasing if the regurgitant volume is large. This hemispherical line of aliasing is termed the *proximal flow convergence region* (Figure 11.15). The diameter of this hemispherical region of aliasing is used in quantitative assessment of regurgitant flow (using the proximal isovelocity surface area technique or 'PISA').



11.15 Left apical four chamber view (zoomed) showing a jet of mitral regurgitation at the closed mitral valve. The colour aliases from blue to yellow at the proximal flow convergence region (white arrow). The 'neck' of the jet (vena contracta, black arrow) corresponds with the regurgitant orifice diameter.

Technique	Feature	Normal	Myxomatous mitral valve disease		
			Mild	*Moderate*	*Severe*
2D	Valve prolapse	None	Just extending beyond annular line	Partial prolapse beyond annular line	Large segments prolapsing with fixed distortion
	Flail leaflets	None	None	None	±
	LA size	Normal	Normal	Normal/mildly dilated	Dilated
Colour Doppler	Jet position	None or trace	Single central	Multiple or eccentric	Filing chamber
	Jet area	None or trace	Narrow or short	Less than half LA area	More than half LA area
	Vena contracta width	N/A	N/A	<2 mm	>2 mm
	Proximal flow convergence	N/A	None	None	Present
Spectral Doppler	Mitral E wave velocity	<1.2 m/s	<1.2 m/s	<1.2 m/s	>1.2 m/s

11.14 Grading of mitral valve severity in MMVD.

The regurgitant flow meets a bottle-neck at the valve's regurgitant orifice, which forms the 'neck' of the regurgitant jet. The width of this 'neck' is called the *vena contracta*, and its width corresponds with the size of the regurgitant orifice. It is difficult to obtain a view of the regurgitant orifice that includes the vena contracta, but this is most easily achieved with left apical views. The vena contracta width is not affected by colour Doppler gain controls or eccentric jets.

Pressure gradients and flow rates: The larger the systolic regurgitant volume, the greater the forward flow of blood across the mitral valve in diastole, so that with severe mitral regurgitation the velocity of early mitral filling (*E wave*) is increased (>1.2 m/s).

Tricuspid regurgitation

Valve lesions: Many of the principles used in mitral regurgitation also apply to tricuspid regurgitation. MMVD can also affect the tricuspid valve, sometimes causing prolapse and flail (see Figure 11.17).

Chamber remodelling: Severe tricuspid regurgitation results in an increase in right atrium (RA) and right ventricle (RV) diameters.

Disturbed flow: The jet of tricuspid regurgitation can be viewed with colour flow Doppler in the same way as mitral regurgitation.

Pressure gradients and flow rates: The main clinical importance of tricuspid regurgitation is in assessing *pulmonary hypertension* (Figure 11.16) (Serres *et al.*, 2007). Although not always present with pulmonary hypertension, tricuspid regurgitation blood flow velocity allows estimation of RV pressure (which is equivalent to pulmonary artery pressure in the absence of pulmonic stenosis).

Aortic regurgitation

Aortic regurgitation is rarely clinically significant in small animals unless infective endocarditis affects the aortic valve, or a ventricular septal defect is present and an aortic valve leaflet prolapses into the defect.

Valve lesions: Causative lesions such as aortic endocarditis can usually be imaged with 2D echocardiography. Sometimes myxomatous valve degeneration also affects the aortic valve, resulting in diffuse thickening and mild aortic regurgitation.

Chamber remodelling: Severe aortic regurgitation may cause an increase in LV volume.

Disturbed flow: One of the best ways to assess the severity of aortic regurgitation is to measure the width of the aortic insufficiency jet at the valve leaflets (vena contracta) relative to the aortic valve diameter.

Pressure gradients and flow rates: The rate of deceleration of the aortic insufficiency jet is related to equilibration of pressures across the aortic valve (i.e. the severity of aortic regurgitation). More rapid deceleration indicates more severe aortic regurgitation.

Pulmonic regurgitation

Pulmonic regurgitation is normal in many dogs and is usually without any haemodynamic significance. Pulmonic regurgitation jet velocity may be useful when assessing severity of pulmonary hypertension, as the pressure gradient across the pulmonic valve gives some indication of mean or diastolic pulmonary artery pressures (see Figure 11.16).

Valvular stenosis

Aortic stenosis

Subvalvular and/or valvular lesions are usually evident on 2D images with moderate to severe aortic stenosis.

Chamber remodelling: LV hypertrophy may be appreciated on 2D or M-mode images.

Disturbed flow: Variance begins at the site of stenosis (e.g. the LV outflow tract with subaortic stenosis, and at the valve with valvular stenosis). Mild aortic regurgitation is often also present.

Pressure gradients and flow rates: Severity of aortic stenosis is generally measured in terms of the magnitude of pressure gradient across the aortic valve, calculated using the simplified Bernoulli equation (see Figure 11.16). It should be noted that pressure gradients are affected by flow as well as the stenotic valve area. This means the *pressure gradient will be underestimated under low-flow states* (i.e. with systolic dysfunction or under anaesthesia).

Condition	Measurements necessary	Formula	Normal values (mmHg)
Pulmonary hypertension	Peak TR velocity	Systolic PA pressure = (4 x TR velocity^2) + RA systolic pressure	<32
	Peak PR velocity	Mean PA pressure = 4 x PR velocity^2	<20
Aortic stenosis	Peak aortic valve velocity	Aortic valve PG = 4 x aortic valve velocity^2	Mild: <50 Moderate: 50–80 Severe: >80
Pulmonic stenosis	Peak PA velocity	PA PG = 4 x PA velocity^2	Mild: <50 Moderate: 50–80 Severe: >80

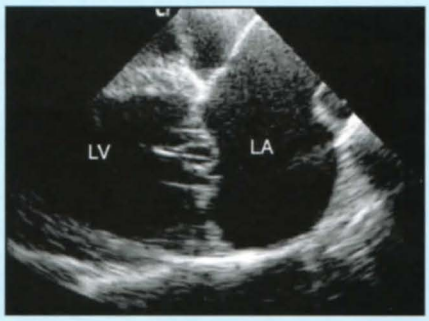
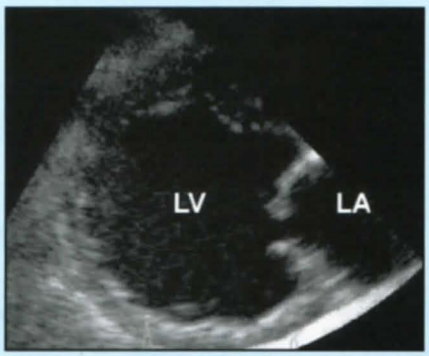
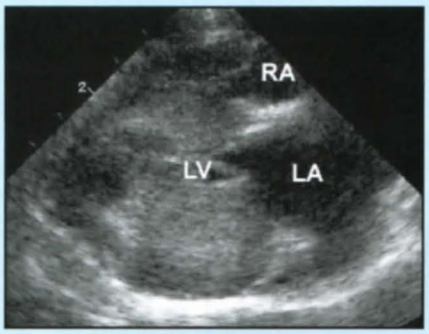
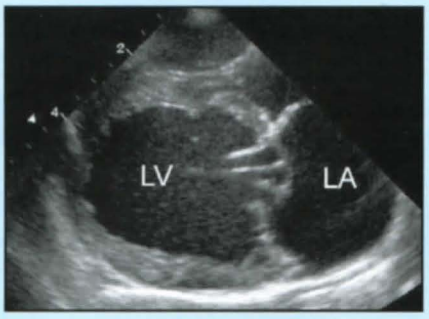
11.16 Calculation of common pressure gradients using Doppler echocardiography. PA = Pulmonary artery; PG = Pressure gradient; PR = Pulmonic regurgitation; TR = Tricuspid regurgitation.

Pulmonic stenosis

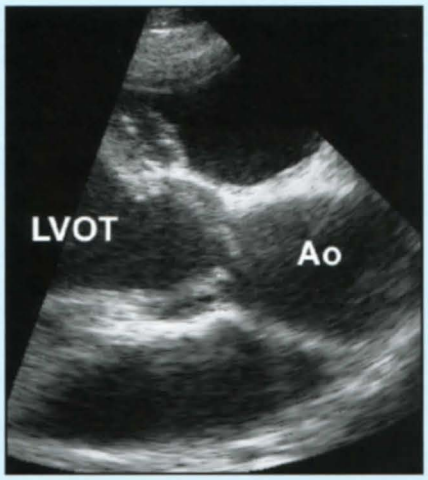
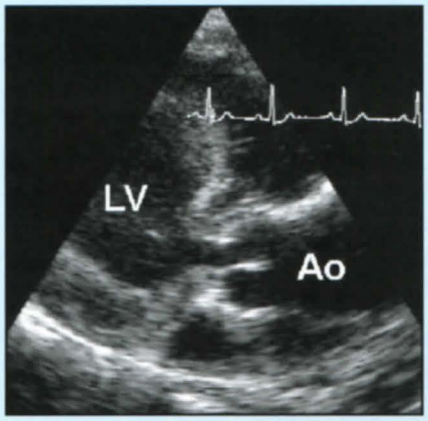
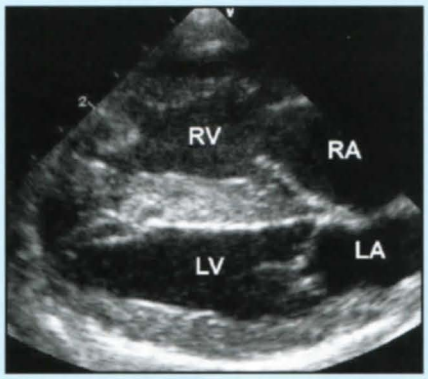
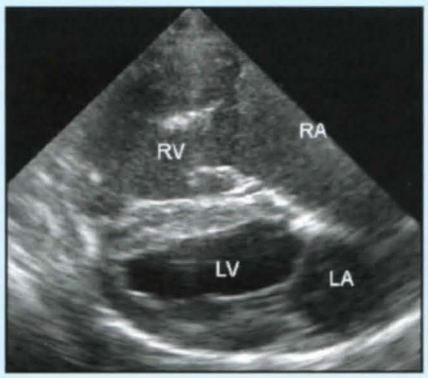
The same techniques used for aortic stenosis are applicable to pulmonic stenosis.

Interpretation

The above measurements may be helpful when applying echocardiography to clinical cases, in conjunction with other diagnostic findings. Although a standard approach builds up expertise in the various views, it may be necessary to alter the echocardiography study protocol according to findings. In particular, the different causes of lesions and chamber remodelling should be considered *during* the echocardiography study, which will guide the echocardiographer in selection of the most appropriate measurements. The most common differential diagnoses for cardiac lesions and different patterns of chamber remodelling are given in Figure 11.17.

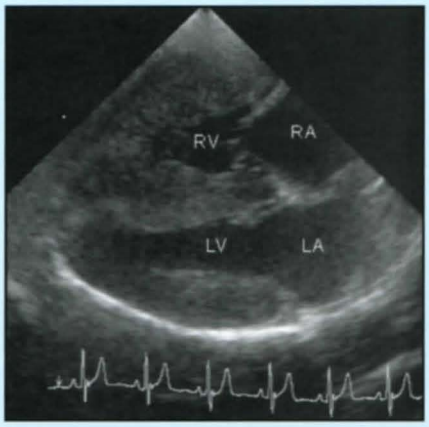
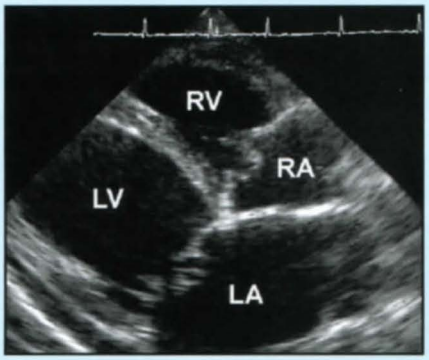
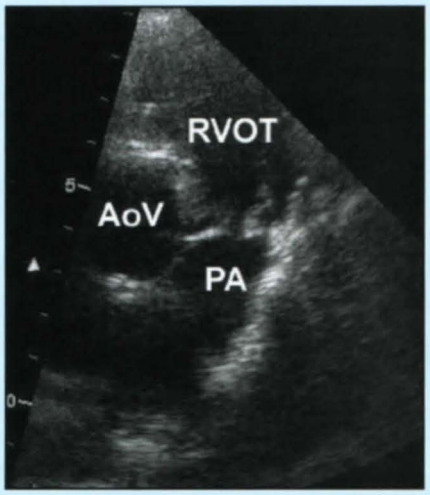
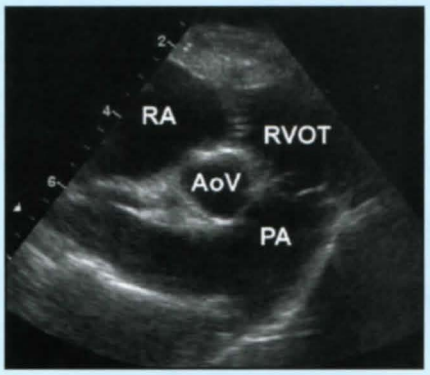
Abnormality	Image	Differential diagnosis
LA dilatation		Volume overload: • Mitral regurgitation (see image) • Left-to-right patent ductus arteriosus or ventricular septal defect Congenital mitral stenosis LV systolic dysfunction: • Dilated cardiomyopathy LV diastolic dysfunction: • Hypertrophic cardiomyopathy • Restrictive cardiomyopathy • Unclassified cardiomyopathy
LV dilatation		LV volume overload: • Mitral regurgitation • Left-to-right patent ductus arteriosus or ventricular septal defect LV systolic dysfunction: • Dilated cardiomyopathy (see image) • End-stage hypertrophic cardiomyopathy
LV hypertrophy		LV pressure overload: • Aortic stenosis • Systemic hypertension Idiopathic: • Hypertrophic cardiomyopathy (see image)
Mitral valve abnormalities		Myxomatous mitral valve disease (see image) Infective endocarditis Congenital mitral dysplasia

11.17 Differential diagnosis for abnormalities of chamber dimensions and valves. LA = Left atrium; LV = Left ventricle; RA = Right atrium. (continues) ▶

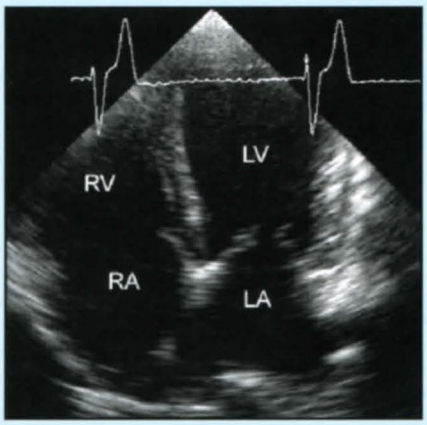
Abnormality	Image	Differential diagnosis
Aortic valve abnormalities		Congenital aortic stenosis (see image) Infective endocarditis Myxomatous valve disease
Aortic valve dilatation		Aortic stenosis with post-stenotic dilatation (see image) Systemic hypertension Annuloaortic ectasia
RA dilatation		RV volume overload: • Tricuspid regurgitation • Left-to-right atrial septal defect Congenital tricuspid stenosis RV systolic dysfunction: • RV cardiomyopathy RV pressure overload: • Pulmonary hypertension • Pulmonic stenosis (see image)
RV dilatation		RV volume overload: • Tricuspid regurgitation (see image; tricuspid dysplasia) • Left-to-right atrial septal defect RV systolic dysfunction: • RV cardiomyopathy Acute RV pressure overload: • Pulmonary hypertension

11.17 (continued) Differential diagnosis for abnormalities of chamber dimensions and valves. Ao = Aorta; LA = Left atrium; LV = Left ventricle; LVOT = Left ventricular outflow tract; RA = Right atrium; RV = Right ventricle.

(continues) ▶

Abnormality	Image	Differential diagnosis
RV hypertrophy		RV pressure overload: • Pulmonary hypertension (see image) • Pulmonic stenosis • Double-chambered RV
Tricuspid valve abnormalities		Myxomatous valve disease (see image) Congenital tricuspid dysplasia Distortion of tricuspid valve by RV chamber remodelling
Pulmonic valve abnormalities		Congenital pulmonic stenosis (see image)
Pulmonary artery dilatation		Pulmonic stenosis with post-stenotic dilatation Left-to-right patent ductus arteriosus or ventricular septal defect Pulmonary hypertension (see image)

11.17 (continued) Differential diagnosis for abnormalities of chamber dimensions and valves. AoV = Aortic valve; LA = Left atrium; LV = Left ventricle; PA = Pulmonary artery; RA = Right atrium; RV = Right ventricle; RVOT = Right ventricular outflow tract. (continues) ▶

Abnormality	Image	Differential diagnosis
Dilatation of all four chambers		Dilated cardiomyopathy Atrial fibrillation High-grade atrioventricular block (see image) Anaemia Hyperthyroidism

11.17 (continued) Differential diagnosis for abnormalities of chamber dimensions and valves. LA = Left atrium; LV = Left ventricle; RA = Right atrium; RV = Right ventricle.

References and further reading

Boon JA (1998) *Manual of Veterinary Echocardiography.* Williams & Wilkins, Baltimore

Brown DJ, Rush JE, MacGregor J *et al.* (2003) M-mode echocardiographic ratio indices in normal dogs, cats, and horses: a novel quantitative method. *Journal of Veterinary Internal Medicine* **17**, 653–662

Cornell CC, Kittleson MD, Della Torre P *et al.* (2004) Allometric scaling of M-mode cardiac measurements in normal adult dogs. *Journal of Veterinary Internal Medicine* **18**, 311–321

Dukes-McEwan J, Borgarelli M, Tidholm A, Vollmar AC and Haggstrom J (2003) Proposed guidelines for the diagnosis of canine idiopathic dilated cardiomyopathy. *Journal of Veterinary Cardiology* **5**, 7–19

Hansson K, Haggstrom J, Kvart C and Lord P (2002) Left atrial to aortic root indices using two-dimensional and M-mode echocardiography in cavalier King Charles spaniels with and without left atrial enlargement. *Veterinary Radiology & Ultrasound* **43**, 568–575

Schober KE and Baade H (2000) Comparability of left ventricular M-mode echocardiography in dogs performed in long-axis and short-axis. *Veterinary Radiology & Ultrasound* **41**, 543–549

Serres F, Chetboul V, Gouni V *et al.* (2007) Diagnostic value of echo-Doppler and tissue Doppler imaging in dogs with pulmonary arterial hypertension. *Journal of Veterinary Internal Medicine* **21**, 1280–1289