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Colour flow Doppler echocardiography in normal horses

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Abbreviations

RA	right atrium
TV	tricuspid valve
RV	right ventricle
IVS	interventricular septum
LA	left atrium
MV	mitral valve
LV	left ventricle
PA	pulmonary artery
PV	pulmonary valve
AO	aorta
AOV	aortic valve
AR	aortic regurgitation
PAP	pulmonary artery pressure
LVOT	left ventricular outflow tract
RVOT	right ventricular outflow tract

Summary

Colour flow Doppler echocardiography is a technique that is used with two-dimensional (2-D) echocardiography to study blood flow patterns in the heart and blood vessels. This method was used to define normal flow patterns and to evaluate valvular function in 40 clinically normal Thoroughbred and Thoroughbred cross horses. Flow patterns from 10 standardised echocardiographic images were described in relation to anatomic landmarks and timing during the cardiac cycle. Consistent intracardiac flow patterns were identified in the normal horses. High velocity flow signals or regurgitant jets were recorded at the tricuspid (77.5%), mitral (67.5%), aortic (47.5%) and pulmonary valves (40%) in clinically normal horses. Most of these signals were transient, and many were associated with valve closure.

This study demonstrates that colour flow Doppler echocardiography is a sensitive technique for the detection of intracardiac flow in horses. It will provide a basis by which to compare studies in horses suspected of having valvular heart disease.

Introduction

There is a high incidence of functional and pathological murmurs in horses (Glendinning 1964; Patterson *et al.* 1965; Muylle and Oyaert 1980). The differentiation of these murmurs can be difficult (Glendinning 1972; Reef 1991) especially systolic murmurs (Miller and Holmes 1985), which can arise from a number of sites and are the most common. Doppler echocardiography has been shown to be a sensitive indicator of abnormal blood flow in man and is the only noninvasive method of recording valvular regurgitation (Krayenbuehl and Jenni 1985). Doppler colour flow mapping records the velocity and direction of flow from multiple adjacent sampling sites. This information is then colour coded and overlaid on 2-D (Goldberg *et al.* 1988; Durell 1990) or M-mode echocardiographic images (Monaghan and Mills 1989; Mitchell 1990). It allows rapid screening of cardiac chambers for abnormal flow (Cooper *et al.* 1989) and the detection of small eccentric jets that are easily missed by continuous wave or pulsed wave Doppler echocardiography (Monaghan and Mills 1989). In man, Doppler techniques are so sensitive in the detection of regurgitant flow that physiological retrograde flow disturbances are frequently detected in normal subjects (Yock *et al.* 1984). The widespread use of Doppler echocardiography in human medicine initially resulted in an 'epidemic' of valvular regurgitation (Rahko 1989). It is, therefore, important that physiological flow patterns be distinguished from pathological valvular regurgitation. Reef (1990) has described the use of Doppler colour flow mapping in horses referred for cardiac evaluation; however, there have been no studies describing this technique in normal horses. This paper describes Doppler colour flow studies from standardised 2-D images in normal horses.

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Materials and methods

The study group consisted of 40 Thoroughbred or Thoroughbred cross horses (3 stallions, 21 geldings and 16 mares). The horses, age 2–17 years, weighed 428–648 kg (mean 513 kg) and had no history or evidence of cardiac dysfunction on clinical, echocardiographic and electrocardiographic (ECG) examination. Horses with the following functional murmurs were included as normal: 1) Early systolic ejection murmurs with the point of maximum intensity (PMI) over the aortic valve; 2) short presystolic murmurs (murmur audible between the fourth and first heart sounds) and 3) early (proto-) diastolic murmurs (murmur audible between the second and third heart sounds). One or more functional murmurs were present in 62.5% of the horses.

A Vingmed CFM 700 ultrasound system (Sonotron Ltd, Bedford, UK) with a 2.25 MHz annular phased array transducer was used for all studies. The equipment constructed first a 2-D image, then overlaid the image with colour flow Doppler information. Flow towards the transducer was colour coded in red, with the faster velocities coded in lighter shades. Flow away from the transducer was colour coded in blue, with the highest velocities coded in the lightest shades. When velocities exceeded the Nyquist limit (half the pulse repetition frequency of the

TABLE 1: Flow patterns observed from the right hemithorax in 40 normal Thoroughbred and Thoroughbred cross horses

Location	Systole 1	Systole 2	Early diastole	Mid-diastole	Late diastole
RA	**No flow (22)** Red (18)	**Red (36)** No flow (4)	**Red (40)**	**No flow (29)** LVB (4) LVB/R (4) LVR (3)	**Red (32)** No flow (8)
TV	**No flow (35)** Blue (5)	**No flow (40)**[a]	**Red(40)**	**No flow (26)** LVB (13) LVR (1)	**Red (32)**[b] No flow (6) Red Al (2)
RV inlet (LAx)	**No flow (39)** Red (1)	**No flow (40)**	**Red (36)** Red A1 (2) R/B (2)	**No flow (28)** LVB (8) LVR (2) LVR/B (2)	**Red (31)** R/B (3) No flow (4) Red Al (1) LVB (1)
RV inlet (SAx)	**No flow (21)** Blue (19)[c]	**No flow (23)** Blue (5) Blue Al (12)	**Red (30)**[d] B/R (8) Blue (2)	**No flow (25)** Red (5) Blue (3) LVB (3) R/B (3) Red Al (1)	**Red (32)**[e] B/R (4) No flow (3) Red Al (1)
RV outlet	**Blue (36)** Blue Al (4)	**Blue Al (40)**[f]	**No flow (26)** Blue (6)[g] LVB (4) Red (4)	**No flow (40)**	**No flow (35)** LVB (2) Red (2) R/B (1)
PV	**Blue (20)** No flow (15) Blue Al (4) R/B (1)	**Blue (21)** No flow (16) Blue Al (3)	**No flow (39)**[h] Red (1)	**No flow (40)**	**No flow (37)** Red (2) Blue (1)

The figures in brackets indicate the number of horses in which the flow pattern was observed. Predominant flow patterns are printed **in bold**. Details of higher velocity flow signals recorded at the valves are described below and detailed in Table 4.
LVB=low velocity blue; LVR=low velocity red; LVB/R=low velocity red and blue; Al=aliased; R/B=red and blue; B/R=blue and red.

[a]17 horses showed blue signals at or immediately following the T wave of the ECG. [b]31 horses showed blue/red 'closure' signals at or immediately following the onset of the QRS complex. [c]In the second half of systole 1, the flow pattern in 9 of th 19 horses showing a blue colour, changed to a blue pattern with aliasing. [d]27 horses showed a blue flow pattern immediately prior to this red flow pattern.[e]Twelve horses showed a blue flow pattern prior to the red flow pattern. [f]All the horses showed a blue pattern without aliasing in the second half of systole 2. [g]In all horses showing a blue pattern, this became red in the second part of early diastole. Colour in 2 horses changed to blue with aliasing before becoming red. [h]Sixteen horses showed a red 'closure' pattern immediately after the T wave of the ECG.

transducer) aliasing occurred, where blood is coded as flowing in the opposite direction. Disturbed flow was depicted by a green colour, allowing it to be clearly distinguished from areas of normal laminar flow (Angelsen *et al.* 1989). The sector angle, depth, quality and low velocity reject settings were set to achieve a Nyquist limit of 0.7 m/s with a frame rate of between 9 and 12 frames/s. The amplification (gain) of the colour signal was set at the level which just failed to produce colour artefacts within the sector image. The colour settings were kept constant for all horses imaged.

Colour flow studies were recorded from all horses using the following standardised 2-D images, as described by Long *et al.* (1992).

1) *Right parasternal views*: a) long-axis image of the ventricular inlets (reference view); b) tipped view of the left ventricular inlet and outlet; c) long-axis view of the aorta; d) dorsal location right ventricular inlet view; e) apical view of the ventricular inlets; f) short-axis view at the pulmonary artery level and g) angled view of the right ventricular outflow tract.

2) *Left parasternal long axis views*; a) left ventricular inlet (reference view); b) apical view of the left ventricular inlet and c) 5-chambered view.

The timing of events within the cardiac cycle was determined from a frame change indicator which displayed the exact duration of each colour frame relative to the ECG. Each frame constituted between 83 and 111 ms of flow information. When more accurate timing of events was required the ECG was compared to a colour M-mode or spectral Doppler recording taken from the area of interest.

The colour flow patterns within the chambers were analysed in a qualitative manner relative to anatomic location and timing within the cardiac cycle. Systole was divided into 2 phases. Systole 1 corresponded to the first half of the ejection period and systole 2 the second half. Diastole was divided into 3 phases: Early diastole, extending from the end of systole to the end of the rapid filling phase of the ventricle; mid-diastole (diastasis) representing the period immediately following the rapid filling phase of the ventricle to the inscription of the P wave of the ECG; and presystole beginning at the P wave and ending during the first third of the QRS complex of the ECG. For each horse at least 10 cardiac cycles were analysed frame by frame from videotape recordings of each of the 10 image planes studied.

Discrete high velocity signals or jets recorded at the level of the 4 heart valves were measured using electronic callipers contained within the echocardiographic system. The width (at the valve), length and area of the 3 largest signals were measured and the average value used for analysis. Linear dimensions were measured to the nearest 0.06 cm. Area measurements were recorded by manual planimetry and were measured to the nearest 0.01 cm^2. The duration of the regurgitant flow was estimated from the number of colour frames in which it persisted and was compared to the duration of systole. The onset time of the signal was determined by measuring the distance moved by the frame rate indicator, between the onset of the QRS complex and the onset of the signal. Time was then calculated from the frame rate and the distance moved by the frame indicator in 1 second.

TABLE 2: Flow patterns observed from the left hemithorax in 40 normal Thoroughbred and Thoroughbred cross horses

Location	Systole 1	Systole 2	Early diastole	Mid-diastole	Late diastole
LA	**No flow (38)** LVB (2)	**No flow (33)** Red (5)[a] Blue (2)	**Red (39)** Red Al (1)	**No flow (34)** Red (4) LVB (2)	**No flow (21)** Red (19)
MV	**No flow (40)**	**No flow (40)**	**Red (37)** Red Al (3)	**No flow (31)** LVB (5) Red (3) Red Al (1)	**Red (32)** No flow (5) Red Al (1) LVB (1) R/B (1)
LV inlet	**No flow (40)**	**No flow (40)**	**Red (32)** Red A1 (8)	**No flow (22)** Red (12) Red Al (2) LVR/B (2) LVB (2)	**Red (28)** No flow (11) Red Al (1)
LV outlet	**Blue Al (29)** Blue (11)	**Blue Al (34)** Blue (6)	**Red (30)**[b] Blue (6)[c] No flow (4)	**No flow (33)** LVB (4) Red (2) B/R (1)	**No flow (33)** LVB (2) Red (3) LVB/R (2)
Aov	**Blue Al (29)** Blue (11)	**Blue Al (34)** Blue (6)	**No flow (36)**[d] Red (4)	**No flow (39)** LVR (1)	**No flow (36)** LVB (3) Red (1)

The figures in brackets indicate the number of horses in which the flow pattern was observed. Predominant flow patterns are printed in bold. Details of higher velocity flow signals recorded at the valves are described below and detailed in Table 4.
LVB=low velocity blue; LVR=low velocity red; LVB/R=low velocity red and blue; Al=aliased; R/B=red and blue; B/R=blue and red.

[a]Two of the horses showing a red pattern developed a blue flow pattern in the second half of systole 2. [b]In 6 of the 30 horses showing a red flow pattern, this changed to a blue flow pattern in the second part of early diastole. [c]Three horses showing a blue flow pattern changed to a blue/red pattern in the second part of early diastole. [d]Fifteen horses showed a red closure pattern immediately after the T wave of the ECG. [e]Eight horses showed a red pattern immediately before the onset of the QRS complex.

Statistical analysis of results

Descriptive statistics by valve site were determined for the length, width, area, and time of onset of any discrete signal or jet. The duration of the jet or high velocity signal relative to the duration of electrical systole was determined for high velocity systolic flow signals. Differences in age between groups were determined using a Mann-Whitney test.

Results

The flow patterns observed in the 40 normal Thoroughbred and Thoroughbred cross horses are detailed by transducer position, anatomic location and timing during the cardiac cycle in Tables 1 and 2. These tables do not include the high velocity signals at the valves which are detailed in Table 3. Flow patterns within the right side of the heart (Table 1) were best evaluated from the right parasternal views because these image planes provided the best alignment with flow. Left sided flow dynamics (Table 2) were best appreciated from transducer placements over the left hemithorax. Low flow velocity signals (<0.31 ms) were not recorded in this study due to low velocity reject filters. The principle patterns of flow observed are described below.

Right ventricular filling

Diastolic ventricular inflow patterns could be recorded in the atria, across the atrioventricular valves and within the ventricular inlets and outlets. Most horses showed no flow signals in the right atrium during the first half of systole (Table 1). In the second half of systole a red flow signal, consistent with venous return, appeared in the right atrium (Fig 1). During early diastole, a large intense red signal was recorded in the right atrium, right ventricle and across the open tricuspid valve and into the right ventricle. This signal which ended abruptly was interpreted as the rapid ventricular inflow phase. During mid-diastole either no flow, or very small low intensity flow signals were recorded in the right ventricular inlet. Following the P wave of the ECG an intense red signal compatible with flow caused by atrial contraction was recorded in the right atrium, across the tricuspid valve and in the right ventricle (Fig 2). In some horses, this red inflow signal could not be detected. The precise timing of these flow signals could be readily demonstrated by a colour M-mode recorded from a line through the right ventricle, tricuspid valve and right atrium (Fig 3). During diastole no consistent flow signal above 0.31 ms was observed in images of the right ventricular outflow tract. However, just proximal to the outflow tract, an early diastolic dark blue signal was detected, immediately followed by a much larger red signal indicating rapid ventricular filling (Fig 4). The blue pattern subsequently disappeared. In some horses, the blue and red patterns appeared simultaneously. In late diastole, following the P wave, atrial contribution to filling was evident as a red signal on the ventricular side of the tricuspid valve proximal to the supraventricular crest.

Left ventricular filling

Recordings from the left parasternal long-axis (reference) and apical views, showed predominantly no flow in the left atrium or ventricular inlet throughout systole (Table 2). In early diastole, a red signal was recorded within the left atrium and across the mitral valve annulus into the left ventricle. In some horses, this red flow signal showed aliasing in its central core. Similar to findings from the right side of the heart, no flow exceeding 0.31 ms was recorded in most horses during mid-diastole. After the P wave, a red signal was evident crossing the mitral valve and entering the left ventricle. Images of the left ventricular outflow tract during diastole demonstrated a red pattern, corresponding to rapid ventricular filling. This signal subsequently changed to a blue colour during the latter part of early diastole. In some horses an initial blue colour was seen, which changed to a blue and red colour.

A large blue diastolic regurgitant flow signal was detected at

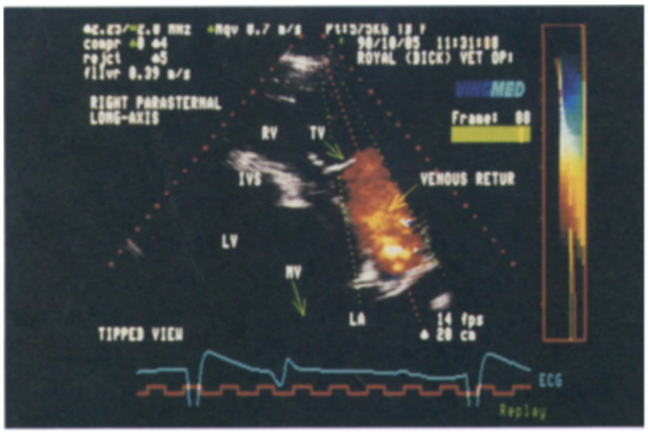

Fig 1: Colour flow Doppler study from a right parasternal long-axis view showing a red flow signal in the right atrium during the second part of systole. The lighter shades of red represent areas of high velocity flow.

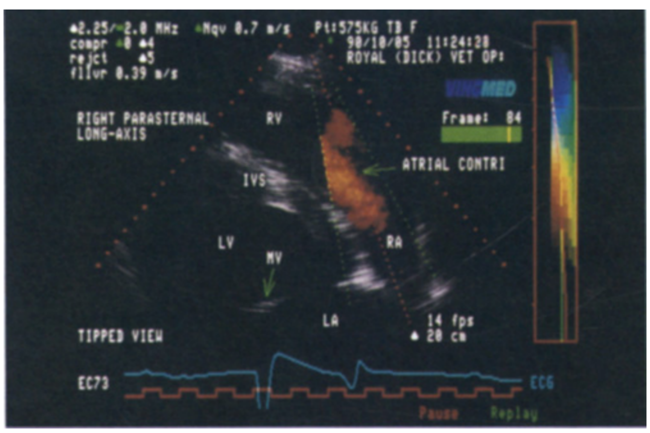

Fig 2: Colour flow Doppler study from a right parasternal long-axis view showing a red flow signal in the right atrium, right ventricle and across the open tricuspid valve following the P wave of the ECG. The lighter shades of red represent a central core of higher velocity flow.

the atrioventricular valves and atria of all horses with second degree atrioventricular block. The regurgitant flow pattern occurred after the nonconducted P wave (Fig 5) and in some cases persisted until the following atrial contraction.

Right ventricular ejection

Right ventricular ejection, displayed as a blue flow signal, was recorded during systole in the right ventricular outflow tract and pulmonary artery. This flow signal changed to blue with a core of signal aliasing in the second half of systole, and finally returned to a blue colour in late systole. Signal aliasing occurred at the level of the supraventricular crest (Fig 6), which was the region best aligned to the axial beam of the transducer.

Left ventricular ejection

During systole, a blue flow signal was seen in the left ventricular outflow tract and aorta in the 5-chambered view. This blue flow signal was aliased in most horses (Fig 7).

Flow patterns at the cardiac valves

High velocity signals or regurgitant jets were recorded at various

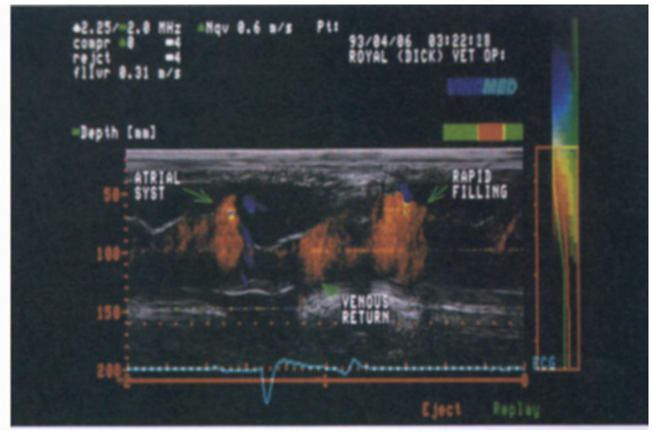

Fig 3: Colour M-mode study recorded from the cursor, shown in Figure 2 as a red dotted line passing through the right ventricle, tricuspid valve and right atrium. The images recorded along this line are displayed on the y axis of the M-mode and are plotted against time on the x axis. The red flow signal on the left of the M-mode image indicates the normal diastolic flow into the right ventricle following the atrial contraction. In the centre of the image a red signal is displayed below the tricuspid valve which represents the venous return during systole. The red flow signal on the right of the image represents flow from the right atrium, across the tricuspid valve into the right ventricle during rapid filling of the ventricle.

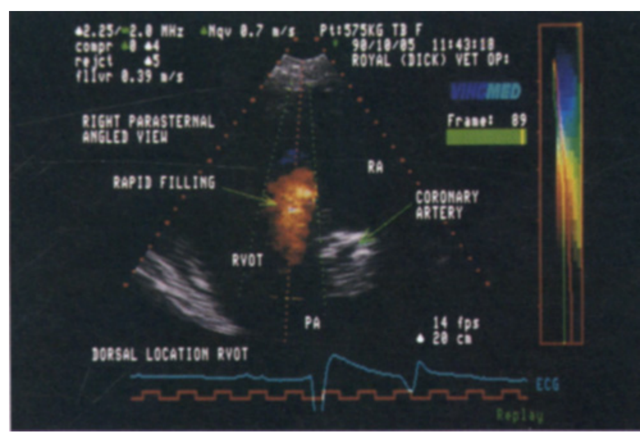

Fig 4: Colour flow study from the right parasternal angled view, dorsal location right ventricular outflow tract. Flow is coded red, moving towards the transducer (top of image), during diastole. A central core of higher velocity flow is coded in lighter shades of red.

cardiac valves in a number of horses. Specific details of these flow patterns (width, length, area, time of onset and duration) are given in Table 3.

Tricuspid valve: Thirty-one of the 40 normal horses (77.5%) showed a high velocity signal at the tricuspid valve either immediately following the onset of the QRS complex (29 horses) or immediately prior to the onset of the QRS complex (2 horses). The flow pattern was brief, 110 ms or less, persisting for 1 frame only, in 27 horses (67.5%) and for more than 1 frame in 4 horses (10%). The signal was recorded on the right atrial side of the tricuspid valve either as a blue regurgitant jet or an aliased red/blue closure signal (Fig 8). The closure signal was present in 22 horses (55%) whereas 9 horses (22.5%) showed a closure noise and a discrete blue jet. There was no significant age difference between the horses showing a high velocity signal at the tricuspid valve and those showing no signal (P=0.38).

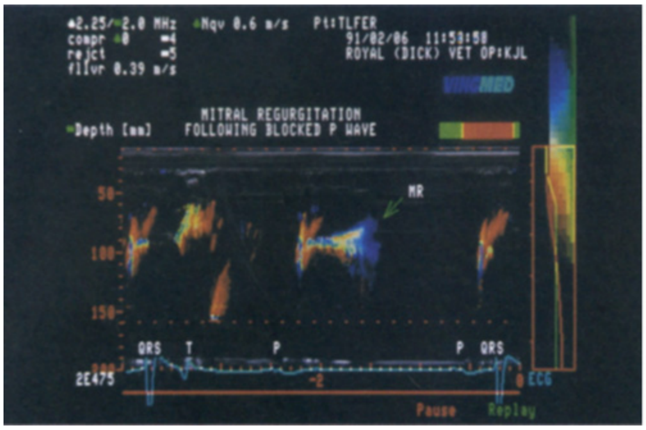

Fig 5: Colour M-mode study recorded from a single imaging line passing through the left ventricle, mitral valve and left atrium. In the centre of the image a red aliased signal indicates flow due to a nonconducted atrial contraction. To the right of this signal a blue signal (MR) with an aliased core indicates diastolic mitral regurgitation, following the blocked P wave.

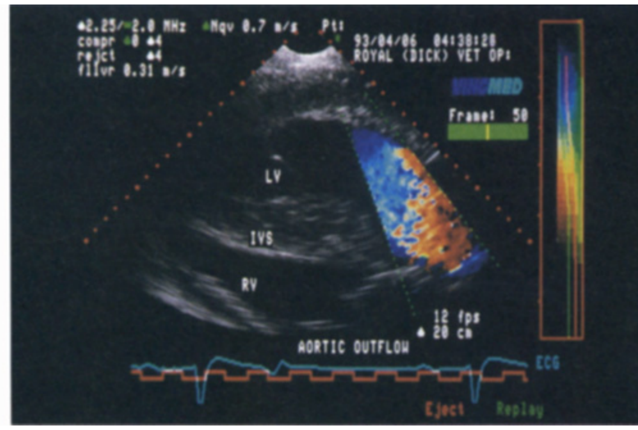

Fig 7: Colour flow Doppler study of the aortic outflow in systole from a left parasternal 5-chambered view. The flow signal is coded blue in the left ventricle but is aliased (coded red) in the left ventricular outflow tract and aorta.

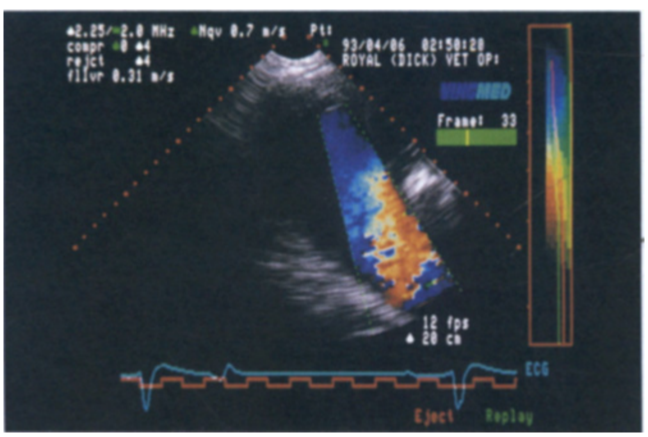

Fig 6: Colour flow study from the right parasternal angled view, dorsal location right ventricular outflow tract. Blood flow in the right ventricle, at the top of the colour sector, is coded blue. As the flow velocity increases as blood flows into the right ventricular outflow tract, flow is coded in lighter shades of blue. At the level of the supraventricular crest the flow velocity exceeds the Nyquist limit and signal aliasing occurs. The aliased signal is coded red.

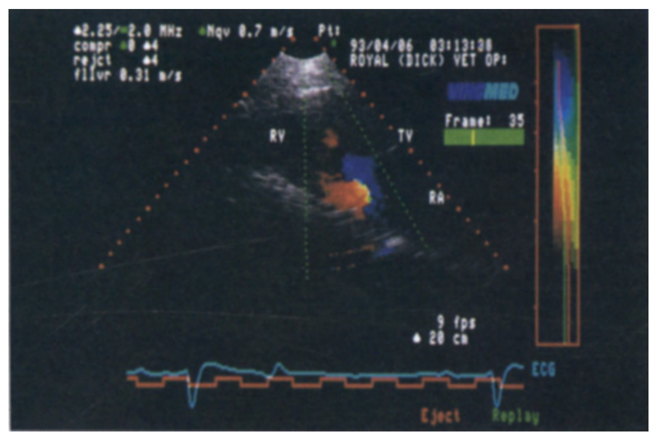

Fig 8: Colour flow study from a right parasternal long-axis view, long-axis aorta, at the onset of systole. The colour flow sector is positioned over the right ventricular inlet. A closure signal coded red and blue with high velocity core is seen at the level of the tricuspid valve.

Seventeen horses (42.5%) showed a blue regurgitant flow pattern at the tricuspid valve immediately following the T wave of the ECG indicating either late systolic regurgitation or movement of the image plane into that of the regurgitant jet.

Mitral valve: Twenty-seven of the 40 normal horses (67.5%) showed a high velocity closure signal or brief regurgitant jet at the mitral valve. This signal occurred with or immediately after the onset of the QRS complex (21 horses) or before the onset of the QRS complex (2 horses). The flow signal was recorded on the left atrial side of the valve either as a distinct blue jet (18 horses, 45%) or as a closure pattern around the valve (9 horses, 22.5%). Five horses showing a distinct jet also had a closure pattern. In these horses the closure pattern (Fig 9) was larger than the subsequent jet (Fig 10) and lasted for only one colour frame. The onset time of the signal was not measured in 4 horses due to technical problems with the ECG. Four horses (10%) showed a blue signal after the T wave. This signal was not measured. There was no significant age difference between the horses showing a high velocity signal at the mitral valve and those showing no signal (P=0.16). In 10 horses (25%), a high velocity pattern occurred after the early diastolic filling pattern, developing as the mitral valve leaflets were drawn together.

Pulmonary valve: Sixteen horses (40%) showed a high velocity closure signal at the pulmonary valve immediately following the T wave of the ECG. The signal was red or blue or both, but always had a green or white core, indicative of disturbed flow or a velocity greater than 0.7 m/s. In one horse a holodiastolic signal was recorded. There was no significant age difference between the group of horses showing a high velocity signal at the pulmonary valve and the group of horses with no signal (P=0.82). Twelve of the 40 normal horses (30%) showed a late diastolic, red regurgitant flow signal on the ventricular side of the pulmonary valve after the P wave. This signal was only measured in 2 horses because in the remaining horses the signal was either too narrow to be measured accurately, or was too weak to be clearly delineated.

Aortic valve: Nineteen horses (47.5%) showed a red flow signal at the aortic valve immediately following the T wave of the ECG. In 11 horses (27.5%) the signal was only present for 1 frame and

TABLE 3: Details of colour flow signals observed at the heart valves in a group of normal horses

	n	Median	Max	Min
Tricuspid valve: presystole/systole				
Length (cm)	31	3.250	5.77	1.08
Width (cm)	31	1.346	3.89	0.53
Area (cm^2)	31	3.636	10.44	0.52
Q-onset (s)	31	0.0450	0.113	-0.040
Dur/Q-T (s)	31	0.2174	0.540	0.170
Mitral valve: presystole/systole				
Length (cm)	27	3.180	9.84	2.02
Width (cm)	27	1.373	2.22	0.57
Area (cm^2)	27	4.260	23.82	1.57
Q-onset (s)	23	0.0610	0.196	-0.072
Q-T (s)	25	0.4000	0.530	0.280
Dur/Q-T (s)	25	0.2083	0.405	0.166
Aortic valve: early diastole/diastole				
Length (cm)	15	3.130	5.47	0.97
Width (cm)	15	0.850	2.28	0.34
Area (cm^2)	15	3.030	10.49	0.26
Pulmonary valve: end systole				
Length (cm)	16	2.105	3.28	1.13
Width (cm)	16	0.885	2.17	0.28
Area (cm^2)	16	1.632	5.11	0.57
Q-onset (s)	16	0.4660	1.200	0.426

Max=maximum value; Min=minimum value; Q-onset=time from the onset of the QRS signal to the onset of the colour flow signal; Dur/Q-T=duration of the colour flow signal divided by the Q-T interval. Time measurements are in seconds. Linear measurements are in cm. Area measurements are in cm^2.

appeared to be a closure noise; however, in 2 horses the signal persisted throughout diastole. In 4 horses in which the signal persisted for more than 1 frame it was too weak or too narrow to be measured. There was no significant age difference between the group of horses showing a red flow signal at the aortic valve and the horses not showing a red signal at this valve (P=0.60). A late diastolic, red signal was recorded on the ventricular side of the valve immediately following the P wave in 8 horses.

Discussion

Doppler colour flow patterns in the cardiac chambers

The flow signals recorded in this study were similar to those described in man (Wittlich *et al.* 1990). The strong red signal in early diastole at the right and left atria, atrioventricular valves and ventricular inlets, represented rapid ventricular filling. Aliased inflow was more common during rapid filling of the left than the right ventricle. As the Nyquist limit remained constant throughout the studies, the blood either entered the left ventricle at a higher velocity, or more accurate alignment with mitral inflow was achieved in this group of horses. Alignment with ventricular inflow was not compared between the two ventricles, as measurement from the 2-D image gives no indication of alignment in the azimuthal plane (Goldberg *et al.* 1988). Reef *et al.* (1989) reported higher flow velocities during rapid filling of the left ventricle (mean 0.7 m/s) when compared to the right ventricle (mean 0.49 m/s), quantitative data supported by this qualitative aspect of the colour flow study. Colour flow studies recorded from the angled view of the right ventricular outflow tract indicated that during ventricular filling, blood flows into the ventricle, flows towards the closed pulmonary valve and then curls back towards the tricuspid valve. A change in the direction of flow was also noted in the left ventricular outflow tract during early diastole.

Reef *et al.* (1989) recorded mean flow velocities of 0.19 m/s at the atrial side of the tricuspid valve and 0.27 m/s at the atrial side of the mitral valve during diastasis. The use of low velocity filters, set at 0.31 m/s in the present study, would have filtered out these signals and some of the signals related to atrial contraction.

In man, a red and a blue signal were recorded in the atria during the second part of systole, suggesting a reversal of atrial filling at the closed tricuspid valve, or 2 separate inflow streams (Wittlich *et al.* 1990). This flow pattern was not observed in horses due, perhaps, to differences in image planes, species differences or because only a small proportion of atrial flow was visualised.

The blue outflow pattern in the left ventricular outflow tract and aorta was aliased in the majority of horses during the first part of systole. Whereas the flow pattern in the right ventricular outflow tract was predominantly blue during the first part of systole, changing to an aliased signal in the second part of systole. This finding suggests that the maximal flow velocity in the pulmonary artery increases later in systole when compared to aortic flow velocities. This is in agreement with the findings of Reef *et al.* (1989) who demonstrated, by pulsed wave Doppler echocardiography, that flow velocities peak earlier in the aorta than in the pulmonary artery. During early diastole, flow in the left ventricular outflow tract was away from the aortic valve. This has also been reported using pulsed wave Doppler echocardiography (Reef *et al.* 1989).

Flow patterns at the heart valves

Flow patterns at the heart valves in the control horses are similar to those described in normal humans, associated with transvalvular regurgitation (Wittlich *et al.* 1990). In man, two distinct types of flow pattern are recognised at normal valves: 1) a flow signal of brief duration associated with valve closure and 2) a regurgitant flow signal of longer duration that is unassociated with valve closure (Sahn and Maciel 1988; Wittlich *et al.* 1990). Brief signals lasting up to 100 ms at the aortic and mitral valve, and signals lasting up to 150 ms at the tricuspid valve are more common than longer regurgitant signals (Wittlich *et al.* 1990). Similarly, brief signals were most common in the present study (Table 3); although, the precise duration of the signals could not be accurately timed using the method employed. In this study, a distinction was made between the bright, high velocity signals recorded on the atrial side of the atrioventricular valves during valve closure and distinct jets directed into the atria. However, it is possible that these are simply two colour flow manifestations of the same physiological flow process producing valve closure. It is also possible that these signals indicate true valve regurgitation rather than physiological backflow. Horses were included as normal on the basis of echocardiographic and auscultatory findings, *post mortem* examinations were not undertaken. Signals regarded as being present for only one frame may have been of any duration up to approximately 110 ms. This prevents direct comparisons of this study with previous human studies. Difficulty has also been reported in comparing results from the various human studies (Berger *et al.* 1989; Choong *et al.* 1989) where different methods or criteria were used for the diagnosis of regurgitant flow.

When all signals are considered together, this study shows that valvular regurgitation at the tricuspid valve is more common than at the other heart valves in normal Thoroughbred and Thoroughbred cross horses. This is also the case if only the closure signals or signals less than one frame duration are analysed. Tricuspid regurgitation has been shown to be the regurgitation most commonly associated with valve closure in man (Wittlich *et al.* 1990). However, if regurgitant signals of greater than one frame duration are classified as regurgitation unassociated with valve closure, aortic regurgitation was the most common finding in the normal horses. This is contrary to the findings in man where pulmonary insufficiency (Wittlich *et al.* 1990), tricuspid regurgitation (Berger *et al.* 1989) and mitral regurgitation (Choong *et al.* 1989) have been variously reported as most common. Aortic regurgitation however, was only detected throughout diastole in two horses (5%). This is similar to the findings of Wittlich *et al.* (1990); Choong *et al.* (1989) and Berger *et al.* (1989) in humans, but in contrast to the findings of Yoshida *et al.* (1988) who did not detect aortic regurgitation in any normal subjects. Finally, if one considers discrete jets directed into the atrium as indicative of valvular regurgitation unrelated to normal valve closure, then mitral regurgitation is the most common finding in normal horses. Despite the high incidence of regurgitant signals at the tricuspid valve, these were primarily closure noises rather than discrete jets. In contrast, the signals detected at the mitral valve were more commonly discrete jets. This may reflect a smaller orifice at the mitral valve at the onset of systole, due to more efficient atriogenic closure, or it may be associated with a more rapid rise in ventricular pressure allowing jet formation prior to effective valve closure.

Signals at the tricuspid valve lasted for a greater proportion of systole than signals at the mitral valve. Fifty-one % of signals at the tricuspid valve lasted for greater than 20% of systole, compared to only 30% of the signals at the mitral valve. Berger *et al.* (1989) studying the prevalence of valvular regurgitation in normal human subjects, only included tricuspid and mitral signals that lasted for greater than 50% of systole. Reassessment of the equine data using these criteria shows that there was no evidence of mitral regurgitation in the normal horses and only two horses showed evidence of tricuspid regurgitation. Therefore, it can be observed that the prevalence of valvular regurgitation in horses, as in human subjects, is likely to depend in part on the criteria used to diagnose the condition. If the relatively strict criteria of Berger *et al.* (1989) are employed, then tricuspid and aortic regurgitation are the most common regurgitant signals in normal horses, but are only evident in about 5% of horses studied. If less strict criteria are used, then the prevalence is higher. It should be noted that signals recorded as short duration may have persisted outside of the image plane. This may also explain the occasional recognition of end-systolic tricuspid and mitral regurgitation after the inscription of the T wave. Alternatively, this may have represented a genuine mid or late systolic event as late systolic murmurs of mitral regurgitation have been recognised by the authors and others. Studies of normal humans subjects by transoesophageal Doppler echocardiography, a more sensitive Doppler technique, revealed that all subjects had a regurgitant flow pattern at the mitral and tricuspid valve (Wittlich *et al.* 1990). More detailed examination of the pulmonary valve may have been achieved from a left parasternal inflow/outflow view (Long *et al.* 1992). This may have increased the sensitivity of this study.

The presence of regurgitant flow signals at equine valves may be related to the athletic nature of horses. The prevalence of valvular regurgitation has been shown to be higher in human athletes than in sedentary individuals (Pollak *et al.* 1988; Douglas *et al.* 1989). The horses studied were athletic animals and the prevalence of valvular regurgitation may differ in different types of horses. Perhaps of greatest clinical importance to the present study is the brief duration of the signals recorded in the great majority of horses in this normal group.

Physiological diastolic regurgitation was observed in normal horses at the mitral and tricuspid valves, during second degree atrioventricular block, and was characterised by a blue flow pattern following the nonconducted P wave. Diastolic mitral and tricuspid valve regurgitation have also been reported in human subjects with first and second degree atrioventricular block (Rutishauser *et al.* 1966; Panadis *et al.* 1986; Covalesky *et al.* 1989) and in dogs with second degree atrioventricular block (Darke 1992). A pressure gradient develops between the left ventricle and left atrium after the atrial contraction, causing premature closure of the mitral valve. This closure is not as effective as that caused by an optimally timed atrial and ventricular systole or ventricular systole, and results in valvular regurgitation (Williams *et al.* 1968). This mechanism may explain the diastolic atrioventricular valve regurgitation in the present study.

Tricuspid and mitral regurgitation occurred before the onset of the QRS complex, in 2 horses. The time lag between the onset of electrical activity and the rise in ventricular pressure causing complete closure of the atrioventricular valves is approximately 28 ms (Holmes 1987). The number of horses showing valvular regurgitation, prior to the onset of mechanical systole (defined as 28 ms after the onset of the QRS complex) was determined. Eight horses (20%) showed presystolic tricuspid regurgitation and 6 horses of the 36, in which the onset time was recorded (16.6%) showed presystolic mitral regurgitation. Due to the inaccuracy of assessing onset time from colour frames of limited frame rate, the true prevalence of presystolic regurgitation might actually be higher. Presystolic mitral regurgitation has been recorded in dogs when the P-R interval was lengthened (Williams *et al.* 1968) and it was suggested that the vigour of atrial contraction may alter the effectiveness of atriogenic valve closure in dogs (Sarnoff *et al.* 1962). It is possible that the occurrence of valvular regurgitation in normal horses is related to the long P-R interval in this species. Blood inflow velocities have been shown to be higher at the mitral valve than at the tricuspid valve (Reef *et al.* 1989). Increased velocity of flow through the mitral valve may result in an increased efficiency of atriogenic closure. This may explain the higher incidence of tricuspid regurgitation associated with valve closure, compared to that at the mitral valve in normal horses.

Presystolic regurgitation was also detected across the pulmonary and aortic valve in some horses. Late diastolic accentuation of aortic regurgitation murmurs has been described previously in horses (Smetzer *et al.* 1966). Two-dimensional short-axis studies of the aortic valve at high frame rates have shown apparent opening of the aortic valve between the right coronary and the noncoronary cusp in normal horses following atrial contraction and in some cases of aortic regurgitation an increase in intensity of the Doppler spectrum has been observed following the atrial contraction (K. Blissitt and J. Bonagura, unpublished data). The increase in ventricular volume and pressure following atrial contraction may cause distortion of the semilunar valves allowing valvular regurgitation. Smetzer *et al.* (1966) proposed that atrial systole may exert an external force on the aortic valve annulus leading to an increase in aortic regurgitation.

The size of the regurgitant signal has been used to differentiate physiological regurgitation from pathological regurgitation (Takao *et al.* 1985; Kostucki *et al.* 1986; Choong *et al.* 1989; Berger *et al.* 1989; Reef 1990). Wittlich *et al.* (1990) reported that most normal regurgitant signals are between 1 and 2 cm in length, though this is controversial. In this study, regurgitant signals varied from 0.6 to 9.8 cm in length, the longest signals being evident at the mitral valve. Jet length is related to jet velocity and therefore the pressure gradient across the valve (Switzer *et al.* 1987). The larger jets at the mitral valve may reflect the rapid increase in the transvalvular pressure gradient at this valve during systole. The area of a regurgitant jet depicted by Doppler colour flow mapping is influenced by a large number of variables (Switzer *et al.* 1987; Hoit *et al.* 1989; Chen *et al.* 1990)

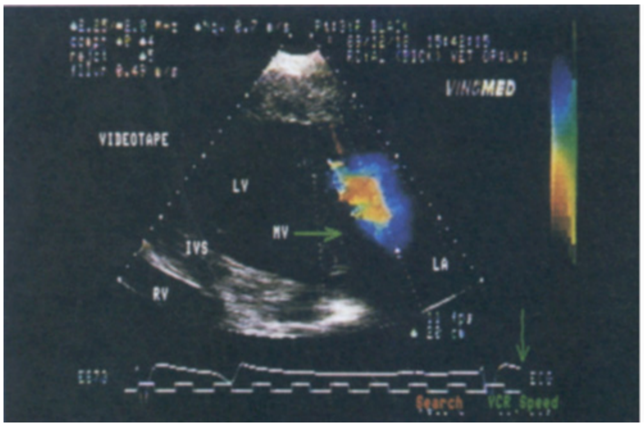

Fig 9: Colour flow study from a left parasternal long-axis apical view. A large blue signal with a central aliased core is shown on the left atrial side of the mitral valve. This colour signal was present for one colour frame only and was then replaced by the small regurgitant jet shown in Figure 10.

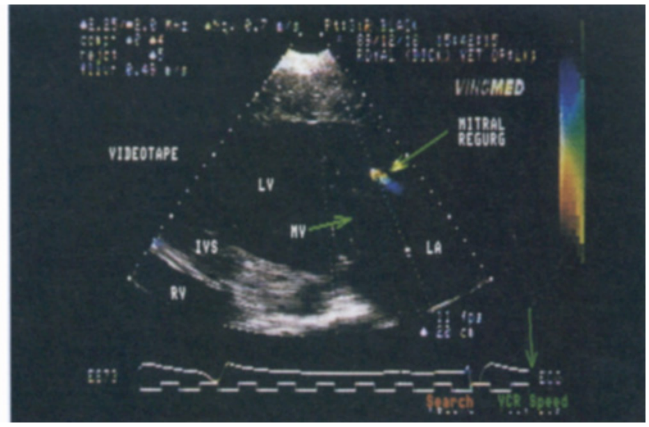

Fig 10: Colour flow study from a left parasternal long-axis apical view. A small blue aliased signal is shown on the left atrial side of the mitral valve. This colour signal followed the large closure pattern shown in Figure 9.

including technical factors (Simpson and Sahn 1991), such as transducer frequency, pulse repetition frequency (Hoit et al. 1989) and signal amplification (Otsuji *et al.* 1987). Some instruments produce consistently larger flow areas for the same degree of regurgitation than other instruments (Sahn *et al.* 1986). While small jets are less likely to be as significant as large jets, the clinical importance of large jets can be over interpreted.

Limitations of study

There is no universally accepted gold standard for identification of abnormal valve function, particularly in horses. In this study, we identified horses as clinically normal when features of cardiac auscultation conformed to those findings long associated with normality in athletic horses (Glendinning 1964, 1972; Patterson *et al.* 1965). Each horse had a normal ECG and 2-D echocardiogram consistent with normal cardiac function. However, it is possible that cardiac murmurs may have been missed. This may explain the presence of regurgitation at the aortic valve throughout systole in 2 horses.

One of the technical factors which may have influenced the results of this study is the use of a single echocardiographic unit. The results obtained with other manufacturer's equipment might have yielded quantitatively or qualitatively different data, as there are no current industry standards for high velocity, disturbed and turbulent flow algorithms. Moreover, the need to filter very low velocity signals to maintain frame rates are a characteristic of some echocardiographic machines, such as that used in the present study, but not others. Filtering of signals less than 0.31 ms probably eliminated low velocity signals, such as those occurring in mid-diastole, or following a relatively weak atrial contraction. However, the authors' experience with other manufacturer's equipment suggests that the major flow patterns were accurately mapped in the current study.

The timing of flow events by a time quantified frame signal, was useful for measuring the approximate duration of backflow and valve closure signals. More accurate timing of the regurgitant flow signals in the present study might have been obtained using colour M-mode. However, it can be difficult to keep the M-mode cursor within a small regurgitant signal, due to movement of the heart during systole (Wittlich *et al.* 1990). This leads to inaccuracy in timing of the duration of the signal (Choong *et al.* 1989). This problem is more obvious when imaging the heart in a long-axis plane rather than a 4-chambered plane because the image tends to move from side to side as the heart contracts and relaxes. Pulsed wave or continuous wave Doppler echocardiography could also be used to time the duration of regurgitant flow signals more accurately, although the limitations noted above also apply. These methods were not employed in this study for the timing of regurgitant signals. Based on this study, relying on a single frame of colour flow information can provide misleading information about the clinical significance of a flow event. The ECG should be recorded during Doppler colour flow imaging, as high velocity or regurgitant signals can be observed during diastole in normal horses. Brief high velocity signals recorded as the mitral valve closed following rapid ventricular filling are a potential source of signal misrepresentation.

Conclusions

This study describes normal Doppler colour flow patterns in horses and provides a basis by which to compare studies in horses suspected of valvular heart disease. In agreement with human studies, regurgitant signals are a common finding at the heart valves in normal horses. However, in most normal horses, the backflow or regurgitant signals are brief, primarily associated with valve closure, with a low incidence of sustained regurgitation unassociated with valve closure. Colour flow Doppler echocardiography has been shown to be a sensitive technique for identifying intracardiac blood flow in horses and may be a useful technique for the diagnosis of cardiac murmurs.

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