Use of quantitative two-dimensional color tissue Doppler imaging for assessment of left ventricular radial and longitudinal myocardial velocities in dogs

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Objective—To determine left ventricular free wall (LVFW) radial and longitudinal myocardial contraction velocities in healthy dogs via quantitative 2-dimensional color tissue Doppler imaging (TDI).

Animals—100 dogs.

Procedure—TDI was used by a single trained observer to measure radial and longitudinal myocardial movement in the LVFW. Radial myocardial velocities were recorded in segments in the endocardial and epicardial layers of the LVFW, and longitudinal velocities were recorded in segments at 3 levels (basal, middle, apical) of the LVFW.

Results—LVFW velocities were higher in the endocardial layers than in the epicardial layers. Left ventricular free wall velocities were higher in the basal segments than in the middle and apical segments. Radial myocardial velocity gradients, defined as the difference between endocardial and epicardial velocities, were (mean ± SD) 2.5 ± 0.8 cm/s, 3.8 ± 1.5 cm/s, and 2.3 ± 0.9 cm/s in systole, early diastole, and late diastole, respectively. Longitudinal myocardial velocity gradients, defined as the difference between basal and apical velocities, were 5.9 ± 2.2 cm/s, 6.9 ± 2.5 cm/s, and 4.9 ± 1.7 cm/s in systole, early diastole, and late diastole, respectively. A breed effect was detected for several systolic and diastolic TDI variables. In all segments, systolic velocities were independent of fractional shortening.

Conclusions and Clinical Relevance—LVFW myocardial velocities decreased from the endocardium to the epicardium and from base to apex, thus revealing intramyocardial radial and longitudinal velocity gradients. These indices could enhance conventional echocardiographic analysis of left ventricular function in dogs. Breed-specific reference intervals should be defined. (*Am J Vet Res* 2005;66:953–961)

Assessment of myocardial performance is important in the diagnosis and treatment of heart disorders. In humans and other animals, conventional echocardiography is a well-established technique for quantitative assessment of heart anatomy and function, allowing measurement of atrial and ventricular dimension, myocardial thickness, and segmental systolic function. Expansion of an echocardiographic examination to include spectral and color flow Doppler imaging enables clinicians to evaluate blood flow direction and velocity, permitting improved assessment and understanding of cardiovascular function and disease. As imaging capabilities expand, the development of more accurate and specific techniques for quantitative evaluation of myocardial function is made possible.

Tissue Doppler imaging (TDI) has been introduced as a new method for analyzing overall as well as segmental myocardial function in small animals.[1] Modification of instrument sensitivity so that high-amplitude and low-velocity ultrasound signals can be detected and processed permits Doppler shift information to be acquired from the moving myocardium, and myocardial wall velocities can be determined.[2] Tissue Doppler imaging enables sensitive, noninvasive, and quantitative in vivo analysis of radial[3-5] and longitudinal[6,7] motion of the **left ventricular free wall (LVFW)**. The repeatability and reproducibility of TDI as a method of assessment of LVFW function have been established in healthy awake cats[8] and dogs.[9] Except in late diastole and in the apical myocardium, where the highest coefficients of variation were recorded (17.8% to 69.2%), these studies revealed that, for most other variables, repeatability and reproducibility of TDI measurements were similar to or slightly higher than those obtained via routine echocardiography. The measurements obtained via TDI were particularly reliable in the endocardial and epicardial segments for the radial motion, and in the basal segments for the longitudinal motion, of the LVFW. The purpose of the study reported here was to prospectively evaluate LVFW motion in healthy dogs; to establish reference values for radial and longitudinal myocardial tissue velocities via **2-dimensional (2-D)** color TDI; and to study the associations of breed, body weight, sex, and age with TDI variables.

Materials and Methods

Dogs—The study population consisted of 100 healthy dogs of different breeds and origins (ie, companion, army,

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and laboratory dogs). Dogs receiving medication or that had a history of heart or respiratory disease were excluded. Owner consent for each dog was obtained before enrollment in the study. All dogs were determined to be healthy on the basis of results of a complete physical examination, arterial blood pressure measurement, ECG, and serum biochemical analyses (ie, glucose, BUN, and creatinine concentrations). Dogs with hyperglycemia (reference interval, 80 to 120 mg/dL), high BUN concentration (reference interval, 8.2 to 33.0 mg/dL), and high creatinine concentration (reference interval, 0.5 to 1.5 mg/dL) or systemic hypertension (systolic arterial pressure > 160 mm Hg or diastolic arterial pressure > 100 mm Hg in unstressed dogs[10]) were excluded from the study. All systolic arterial blood pressure and diastolic arterial blood pressure measurements were made in awake dogs by the same trained observer, via the oscillometric method.[a] A period of acclimatization was allowed for each dog before measuring blood pressure. Dogs were held gently in sternal recumbency. The inflatable cuff was placed around the distal portion of the radius, and several measurements were taken over 5 to 10 minutes to obtain a mean of 5 values. Routine echocardiographic studies and Doppler examinations were performed before the study to confirm normal cardiac anatomy and function in each dog. The procedures used in this experiment were carried out in accordance with a guide for the care and use of laboratory animals[11] and approved by the Animal Use and Care Committee of the National Veterinary School of Alfort.

Conventional echocardiography and Doppler examination—Echocardiographic examination with continuous ECG monitoring was performed on all dogs by the same trained observer with an ultrasound unit[b] equipped with 2.2- to 3.5-MHz and 5.5- to 7.5-MHz phased-array transducers. Ultrasound examinations were performed in awake dogs, gently restrained in the standing position. For each variable, a mean of 3 measurements was determined from 3 consecutive cardiac cycles on the same frame. Ventricular measurements (short-axis view) were taken from the right parasternal location by use of the 2-D–guided M-mode,[12] as recommended by the American Society of Echocardiography.[13] Left ventricular end-diastolic and end-systolic diameters, LVFW thickness, and interventricular septal thickness in diastole and in systole were measured. Left ventricular **fractional shortening (FS)** was calculated. Aortic and left atrial diameters were measured by use of short-axis views obtained from the right-sided parasternal window at the level of the aortic valve where the commissures of the cusps were visible during diastole.[14] The internal short-axis diameter of the aorta was measured at the commissure between the noncoronary and left coronary aortic valve cusps. The left atrium was measured via the same frame, in a line extending from and parallel to the commissure between the noncoronary and left coronary aortic valve cusps. The left atrial diameter-to-aortic diameter ratio was calculated. Pulsed-wave Doppler imaging was used to determine maximal systolic aortic and pulmonary flow velocities and maximal early and late diastolic mitral and tricuspid flow velocities. Aortic and pulmonary flow velocities were recorded via the left apical 5-chamber view and the right parasternal short-axis view at the level of the aortic valve, respectively. Mitral and tricuspid velocities were obtained from the left apical 4-chamber view.

Color TDI examination—Two-dimensional color TDI examinations were performed in awake standing dogs with continuous ECG monitoring by the same trained observer and with the same ultrasound unit[b] as was used for the conventional echocardiographic examinations. In each examination, the gray scale receive gain was set to optimize the clarity of the LVFW endocardial and epicardial boundaries. Segmental myocardial velocities were measured off-line from color Doppler images of the LVFW. Real-time color Doppler images were superimposed on the gray scale with a frame rate ≥ 100 frames/s. The Doppler receive gain was adjusted to maintain optimal coloring of the myocardium, and Doppler velocity range was set as low as possible to avoid aliasing artifact. Digital images were obtained and stored for later review with image-management software.[c] A 2 × 2-mm sampling window was used and a tissue velocity profile recorded for each location. For each myocardial velocity, measurements were made on 3 consecutive cardiac cycles on the same frame, and the mean value was used for statistical analysis. Heart rate was calculated during each TDI examination via an ECG taken during the same 3 cardiac cycles used for the velocity measurements.

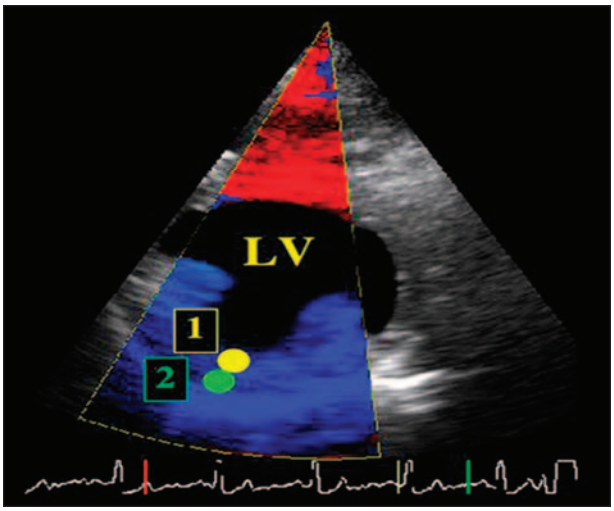

Figure 1—Two-dimensional color tissue Doppler imaging (TDI) view of the heart (right parasternal short-axis view) in a healthy dog. 1 = Location of endocardial sampling segment for radial motion analysis of the left ventricular free wall (LVFW; yellow). 2 = Location of the epicardial sampling segment for radial motion analysis of the LVFW (green). LV = Left ventricle. Tracing at bottom of figure is an ECG recorded at the same time as the TDI.

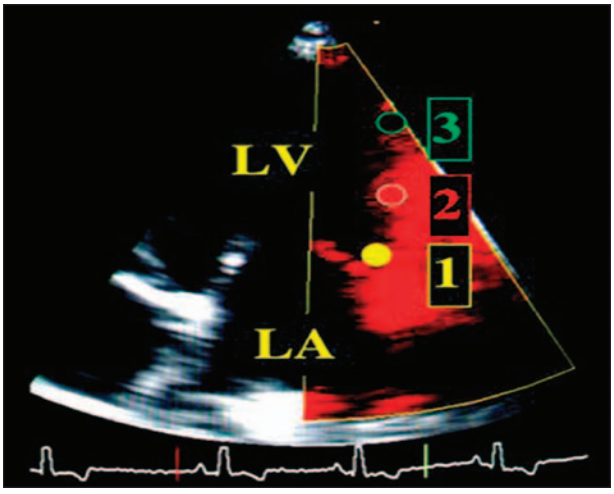

Figure 2—Two-dimensional color TDI view of the heart (left apical 4-chamber view) in a healthy dog. 1 = Location of basal sampling segment for longitudinal motion analysis of the LVFW (yellow). 2 = Location of the middle sampling segment for longitudinal motion analysis of the LVFW (red). 3 = Location of the apical sampling segment for longitudinal motion analysis of the LVFW. LA = Left atrium. Tracing at bottom of figure is an ECG recorded at the same time as the TDI. *See* Figure 1 for remainder of key.

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Quantification of radial left ventricular velocities

Measurement of radial LVFW velocities was performed by use of the right parasternal ventricular short-axis view at a point between the 2 papillary muscles.[8,9] Measurements were made by recording the movement in adjacent endocardial and epicardial segments of the LVFW (**Figure 1**). Simultaneous endocardial and epicardial velocity profiles were obtained during off-line analyses. Radial myocardial velocities were determined in systole, early diastole, and late diastole. Radial **myocardial velocity gradients (MVGs)**, defined as the difference between endocardial and epicardial velocities, were calculated for each phase of the cardiac cycle. **Indexed MVGs (IMVGs)**, defined as MVG divided by LVFW thickness, were also determined.[15]

Quantification of longitudinal LVFW velocities

Measurement of longitudinal LVFW velocities was performed by use of the left apical 4-chamber view.[8,9] Measurements were made of 3 myocardial segments of the internal middle portion of the LVFW (**Figure 2**), including a basal segment, a middle segment (at the level of maximum diastolic opening of the LVFW mitral valve leaflet), and an apical segment (apical third of LVFW). Simultaneous basal, middle, and apical velocity profiles were obtained during off-line analysis. Longitudinal myocardial velocities in systole, early diastole, and late diastole were determined. Longitudinal MVGs, defined as the difference between basal and apical velocities,[3] were calculated for each phase of the cardiac cycle.

Statistical analyses—Data are expressed as mean ± SD, median, and range. Statistical analyses were performed by use of computer software.[d] For measurements of radial motion, the Student paired *t* test was used to compare the endocardial and epicardial velocities. For measurements of longitudinal motion, basal, middle, and apical velocities were compared by use of ANOVA with repeated measures followed, if necessary, by a post hoc Student *t* test with the Bonferroni correction. The same tests were used to compare systolic, protodiastolic, and telediastolic velocities in each segment. General linear modeling is a statistical method that allows description, explanation, and prediction of variation of a quantitative variable with respect to quantitative and qualitative variables. It is considered an extension of ANOVA.[16] The following general linear model was used to study associations between breed, age, body weight, or sex and echocardiographic and TDI variables:

$$Y_{ijkl} = \mu + B_i + A_j + BW_k + G_l + \varepsilon_{ijkl},$$

where Y_{ijkl} is the TDI variable of a dog of breed B_i, age A_j, body weight BW_k, and sex G_l; ε_{ijkl} is the residual term of the model; and μ is the mean general effect. Linear correlations between the heart rate or FS and the different myocardial velocities (endocardial, epicardial, basal, middle, and apical) were examined by use of the Pearson product moment correlation. This test was also used to study the correlation between velocities for each motion. For all comparisons, $P < 0.05$ was considered significant.

Results

Dogs—One hundred dogs (61 sexually intact and 2 castrated males; 31 sexually intact and 6 castrated females) of various ages (3.4 ± 2.1 years; range, 0.4 to 8.8 years), weights (23.8 ± 10.1 kg; range, 6 to 49 kg), and breeds were determined to be healthy by use of physical examination, blood pressure measurement, serum biochemical analyses, and ECG. The study group included 22 Beagles, 19 German Shepherd Dogs, 14 Belgian Malinois, 11 Golden Retrievers, 10 mixed-breed dogs, 7 Labrador Retrievers, 4 Whippets, 3 French Bulldogs, 2 Flat-Coated Retrievers, 2 Cavalier King Charles Spaniels, 1 Border Collie, 1 Bull Terrier, 1 Cocker Spaniel, 1 Fox Terrier, 1 Jack Russell Terrier, and 1 Belgian Tervuren. Normal cardiac function was confirmed by use of conventional echocardiography (**Table 1**).

General left ventricular motion—Velocity profiles included 1 positive systolic wave (S) and 2 negative diastolic waves (E and A, respectively, in early and late diastole; **Figures 3 and 4**). The profiles also included 2 isovolumic phases, the isovolumic contraction phase (from the end of the negative diastolic wave A to the beginning of the positive systolic wave S), and the isovolumic relaxation phase (from the end of the systolic wave S to the first negative diastolic wave E).

Left ventricular radial motion—The heart rate during radial TDI examination was 103 ± 24 beats/min (range, 59 to 171 beats/min). During the cardiac cycle, myocardial velocities (**Table 2**) were significantly higher in the endocardial than in the epicardial segments, which indicated a significant difference in myocardial velocity between the inner and outer layers of the LVFW. Radial MVGs were (mean ± SD) 2.5 ± 0.8 cm/s (range, 1.1 to 4.6 cm/s), 3.8 ± 1.5 cm/s (range, 1.4 to 7.3 cm/s), and 2.3 ± 0.9 cm/s (range, 0.0 to 5.6 cm/s), and radial IMVGs were 1.8 ± 0.7/s (range, 1.0 to 4.6/s),

Table 1—Cardiovascular, standard, and Doppler echocardiographic data obtained in 100 healthy dogs.

Variable	Mean ± SD	Median	Range
Heart rate during clinical examination (bpm)	109 ± 20	110	70–171
Systolic arterial blood pressure (mm Hg)	138 ± 16	140	90–160
Diastolic arterial blood pressure (mm Hg)	80 ± 14	82	46–99
Mean arterial blood pressure (mm Hg)	106 ± 17	107	66–150
Fractional shortening (%)	36.2 ± 3.5	35.9	30.1–49.0
Left atrium diameter-to-aorta diameter	0.90 ± 0.11	0.91	0.52–1.13
Peak aortic velocity (m/s)	1.29 ± 0.22	1.24	0.92–1.88
Peak pulmonary velocity (m/s)	1.05 ± 0.19	1.03	0.50–1.50
Peak mitral early diastolic velocity (E; m/s)	0.87 ± 0.13	0.85	0.58–1.17
Peak mitral late diastolic velocity (A; m/s)	0.61 ± 0.12	0.60	0.39–0.86
Peak mitral E:A ratio	1.46 ± 0.35	1.37	0.92–2.72
Peak tricuspid early diastolic velocity (E; m/s)	0.72 ± 0.11	0.70	0.50–0.98
Peak tricuspid late diastolic velocity (A; m/s)	0.43 ± 0.09	0.41	0.29–0.70
Tricuspid E:A ratio	1.75 ± 0.34	1.73	1.09–2.80

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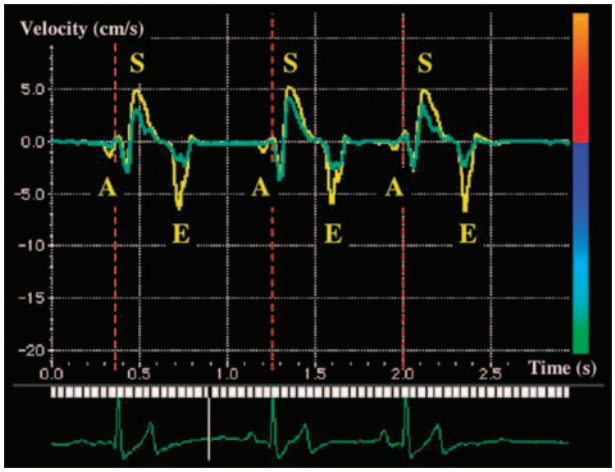

Figure 3—Graph of segmental radial motion of the LVFW of the heart as measured from the right parasternal short-axis view via 2-dimensional TDI in a healthy dog. Notice simultaneous recording of the velocities in the 2 segments (endocardial and epicardial), which reveals that the endocardial layers (yellow curve) are moving more rapidly than the epicardial layers (green curve) in systole and diastole. S, E, A = Peak mean velocity of the LVFW during systole, early diastole, and late diastole, respectively. Tracing at bottom of figure is an ECG recorded at the same time as the TDI.

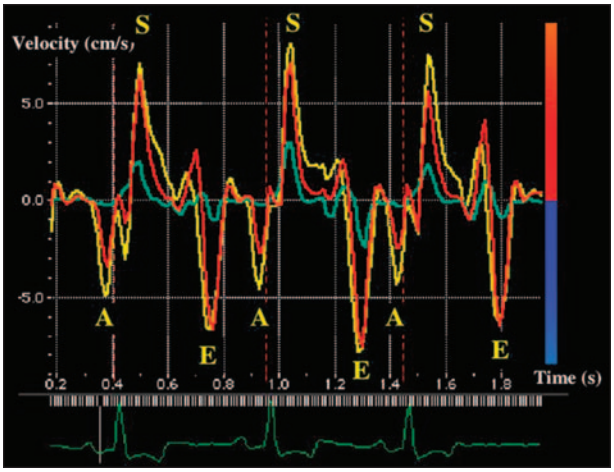

Figure 4—Graph of segmental longitudinal motion of the LVFW of the heart as measured from the left apical 4-chamber view via 2-dimensional TDI in a healthy dog. Notice simultaneous recording of the velocities in the 3 segments (basal, middle, and apical), which reveals that the basal segment (yellow curve) is moving more rapidly than the middle segment (red curve) and much more rapidly than the apical segment (green curve) in systole and diastole. *See* Figure 3 for remainder of key. Tracing at bottom of figure is an ECG recorded at the same time as the TDI.

Table 2—Velocities (cm/s) of radial myocardial contraction in the left ventricular free wall of the heart measured in the endocardial and epicardial segments by use of 2-dimensional color tissue Doppler imaging (TDI) in 100 awake healthy dogs.

Myocardial segment		Systolic wave (S)	Diastolic wave (E)	Diastolic wave (A)	E:A ratio
Endocardial	Mean ± SD	6.4 ± 1.4[a,b]	7.8 ± 2.2[a,c]	4.1 ± 1.4[a,b,c]	2.1 ± 0.9
	Range	3.1–10.8	2.9–14.9	1.4–8.3	1.0–5.1
	Median	6.2	7.6	4.1	1.8
Epicardial	Mean ± SD	3.9 ± 1.1	4.0 ± 1.6	1.9 ± 1.2[b,c]	3.2 ± 3.9
	Range	1.0–6.5	1.4–10.2	0.1–5.6	0.9–36.0
	Median	3.9	3.9	1.7	2.3

S = Peak myocardial velocity during systole. E = Peak myocardial velocity during early diastole. A = Peak myocardial velocity during late diastole.
[a]Significantly ($P < 0.001$) different from value in the epicardial segment. [b]Significantly ($P < 0.001$) different from E wave in the same segment. [c]Significantly ($P < 0.001$) different from S wave in the same segment.

Table 3—Correlations (*r*) between left ventricular myocardial velocities measured in endocardial and epicardial segments of the heart for radial motion and in basal, middle, and apical segments for longitudinal motion via 2-dimensional color TDI in 100 awake healthy dogs.

Motion	Comparison	*r*	*P* value
Radial	S endocardial – S epicardial	0.83	< 0.001
	E endocardial – E epicardial	0.73	< 0.001
	A endocardial – A epicardial	0.78	< 0.001
	S endocardial – E endocardial	0.41	< 0.001
	S endocardial – A endocardial	0.46	< 0.001
	A endocardial – E endocardial	0.33	< 0.001
	S epicardial – E epicardial	0.45	< 0.001
	S epicardial – A epicardial	0.39	< 0.001
	A epicardial – E epicardial	0.58	< 0.001
Longitudinal	S base – S apical	0.57	< 0.001
	E base – E apical	0.32	< 0.01
	A base – A apical	0.47	< 0.001
	S base – E base	0.28	< 0.01
	S base – A base	0.37	< 0.001
	E base – A base	0.51	< 0.001
	S apical – E apical	0.24	< 0.05
	S apical – A apical	0.50	< 0.001
	E apical – A apical	0.44	< 0.001

See Table 2 for key.

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Table 4—Longitudinal left ventricular velocities (cm/s) measured in the basal, middle, and apical segments of the heart via 2-dimensional color TDI in 100 awake healthy dogs.

Myocardial segment		Systolic wave (S)	Diastolic wave (E)	Diastolic wave (A)	E:A ratio
Basal	Mean ± SD	7.6 ± 2.7[a,b,c]	9.0 ± 2.5[a,b]	5.5 ± 1.9[a,b,c,d]	1.8 ± 0.8
	Range	3.0–19.6	3.2–14.7	0.8–10.6	0.9–5.6
	Median	7.5	8.9	5.2	1.6
Middle	Mean ± SD	4.7 ± 2.5[a,c]	7.4 ± 2.7[a]	3.1 ± 1.8[a,c,d]	4.1 ± 5.3
	Range	1.0–13.5	1.7–14.2	0.2–7.7	1.0–35.0
	Median	4.5	7.1	2.8	2.6
Apical	Mean ± SD	1.8 ± 1.5[b]	2.1 ± 1.6[b]	0.6 ± 0.5[b,c,d]	4.7 ± 5.0
	Range	0.1–6.7	0.1–9.4	0.1–2.5	0.5–34.0
	Median	1.5	1.7	0.4	3.7

[a]Significantly ($P < 0.001$) different from value in the apical segment. [b]Significantly ($P < 0.001$) different from value in the middle segment. [c]Significantly ($P < 0.001$) different from E wave in the same segment. [d]Significantly ($P < 0.001$) different from S wave in the same segment.
See Table 2 for remainder of key.

Table 5—Characteristics that were significantly ($P < 0.05$) associated with various standard echocardiographic, Doppler echocardiographic, and TDI variables in 100 healthy dogs and in a subgroup of 66 dogs of breeds in which the breed effect was most pronounced (Beagle [n = 22], German Shepherd Dog [19], Belgian Malinois[14], and Golden Retriever [11]).

Characteristic	Standard and Doppler echocardiographic variables	TDI variables
All dogs		
Breed	LVDD, LVDS	S endo, A endo, S apex, E middle, E/A middle, E/A apex,
Age	E tricuspid	
	E:A mitral	
	E mitral	S apex, E base,
Weight	LVDD, LVDS	
	LVFWD, LVFWS	IMVG in early diastole
		A endo, E/A endo,
Subgroup		
Breed	LVFWD	IMVG in late diastole,
	LVDD, LVDS	E/A endo, A endo
		S base, S middle, S apex,
Age	E:A mitral	
	E mitral	
Weight	LVFWD, LVFWS	IMVG in early diastole
Sex	LVFWD	IMVG in systole,
		A endo, E/A endo, E/A epi

LVDD = Left ventricular diastolic diameter. LVSD = Left ventricular systolic diameter. LVFWD = Left ventricular free wall in diastole. LVFWS = Left ventricular free wall in systole. Mitral = Pulsed-wave Doppler variables of the mitral flow. Tricuspid = Pulsed-wave Doppler variables of the tricuspid flow. Endo = Endocardial segments of the heart. Epi = Epicardial segments of the heart. IMVG = Indexed myocardial velocity gradient for radial motion.
See Table 2 for remainder of key.

4.2 ± 2.0/s (range, 1.4 to 11.6/s), and 2.5 ± 1.1/s (range, 0.0 to 7.8/s) in systole, early diastole, and late diastole, respectively. The highest radial velocities were recorded in the endocardial layers in early diastole, with E significantly higher than both A and S. In the epicardial layers, the diastolic E wave was higher than A, whereas E and S were not significantly different. The lowest velocities were recorded in late diastole, with A significantly lower than E and S in both layers. A significant correlation was observed between endocardial and epicardial velocities during the whole cardiac cycle (**Table 3**). Similarly, in each layer, all velocities were significantly correlated. No correlation was found between heart rate and radial myocardial velocities or between systolic endocardial or epicardial velocities and FS.

Left ventricular longitudinal motion—The heart rate during longitudinal TDI examination was 97 ± 23 beats/min (range, 52 to 171). During the cardiac cycle, myocardial velocities (**Table 4**) were higher in the basal than in the middle and apical segments and were also significantly higher in the middle than in the apical segment, which indicated a significant intramyocardial velocity gradient from the base to the apex of LVFW. Longitudinal MVGs were 5.9 ± 2.2 cm/s (range, 1.9 to 16.6 cm/s), 6.9 ± 2.5 cm/s (range, 0.0 to 13.9 cm/s), and 4.9 ± 1.7 cm/s (range, 0.7 to 9.7 cm/s) in systole, early diastole, and late diastole, respectively. The highest longitudinal velocities were recorded in the basal segment in early diastole, with the E wave significantly higher than either the A wave or the S wave. In the middle segment, the diastolic E wave was significantly higher than the A or S waves, whereas in the apical segment, the E and S waves were not significantly different, although the E wave was higher than the A wave. The lowest velocities

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Table 6—Radial and longitudinal left ventricular velocities (cm/s) of radial and longitudinal motion measured in various segments of the heart via 2-dimensional color TDI in 66 awake healthy dogs of 4 breeds.

		Radial motion			Longitudinal motion			
Breed	Wave	Endocardial segment	Epicardial segment	Heart rate (bpm)	Basal segment	Middle segment	Apical segment	Heart rate (bpm)
Beagle (n = 22)	S	5.4 ± 0.8 [4.2 – 7.0], 5.2	3.0 ± 0.6 [1.8 – 4.3], 2.9	107 ± 19 [72 – 145], 106	6.5 ± 1.6 [4.4 – 9.8], 6.2	4.1 ± 0.9 [2.4 – 6.2], 4.0	1.0 ± 0.6 [0.2 – 2.2], 0.9	97 ± 18 [57 – 135], 96
	E	6.4 ± 2.0 [3.4 – 11.3], 6.0	2.6 ± 0.9 [1.4 – 4.2], 2.6		8.2 ± 1.7 [4.8 – 12.1], 8.0	7.5 ± 1.6 [4.7 – 11.3], 7.2	1.8 ± 1.5 [0.3 – 5.4], 1.3	
	A	3.0 ± 0.7 [1.4 – 4.2], 3.1	0.9 ± 0.5 [0.1 – 2.1], 0.8		5.0 ± 1.5 [2.5 – 8.9], 4.9	3.0 ± 1.7 [0.2 – 7.5], 3.0	0.5 ± 0.4 [0.2 – 1.6], 0.3	
	E:A ratio	2.3 ± 1.0 [1.1 – 4.6], 2.0	4.8 ± 7.2 [1.1 – 36.0], 3.3		1.8 ± 0.8 [1.0 – 4.2], 1.5	5.8 ± 8.3 [1.1 – 35], 2.4	4.5 ± 3.8 [0.8 – 18.0], 3.7	
German Shepherd Dog (n = 19)	S	7.0 ± 1.0 [5.5 – 9.4], 7.1	4.4 ± 0.8 [2.6 – 5.9], 4.3	88 ± 14 [60 – 109], 85	7.9 ± 1.6 [3.0 – 10.0], 8.1	4.7 ± 1.9 [1.0 – 7.9], 5.1	1.8 ± 1.3 [0.1 – 5.4], 1.7	82 ± 16 [54 – 112], 80
	E	8.6 ± 1.7 [5.8 – 12.7], 8.3	5.1 ± 1.7 [2.4 – 10.2], 4.8		9.5 ± 2.5 [5.6 – 14.2], 9.8	7.7 ± 3.3 [1.8 – 14.2], 7.1	2.7 ± 2.2 [0.5 – 9.4], 2.2	
	A	4.4 ± 0.9 [3.0 – 6.3], 4.3	2.2 ± 1.2 [0.7 – 5.6], 2.2		6.3 ± 1.9 [2.2 – 9.9], 6.7	3.3 ± 2.0 [0.5 – 7.1], 2.7	0.6 ± 0.4 [0.3 – 1.3], 0.6	
	E:A ratio	2.0 ± 0.5 [1.0 – 5.1], 2.0	2.7 ± 1.3 [0.9 – 36.0], 2.6		1.6 ± 0.8 [1.1 – 4.5], 1.5	3.0 ± 2.3 [1.1 – 10.8], 2.5	4.8 ± 3.3 [1.1 – 11.5], 4.2	
Golden Retriever (n = 11)	S	7.0 ± 1.3 [4.9 – 9.4], 6.7	4.3 ± 0.7 [2.8 – 5.7], 4.3	115 ± 24 [86 – 171], 119	9.3 ± 4.3 [3.4 – 19.6], 8.7	5.9 ± 2.8 [2.5 – 13.5], 5.4	2.2 ± 0.8 [1.2 – 3.9], 1.9	111 ± 23 [86 – 171], 109
	E	8.5 ± 1.7 [6.1 – 10.8], 8.9	4.7 ± 1.3 [2.9 – 7.2], 5.1		10.1 ± 2.6 [5.5 – 14.1], 9.0	8.9 ± 3.1 [4.3 – 13.2], 9.5	2.2 ± 1.7 [0.2 – 5.6], 1.5	
	A	6.1 ± 1.3 [3.7 – 8.3], 6.3	3.0 ± 1.6 [0.9 – 5.5], 3.0		7.2 ± 1.8 [5.2 – 10.6], 7.0	4.7 ± 1.9 [2.2 – 7.7], 4.1	1.0 ± 0.5 [0.4 – 1.9], 0.9	
	E:A ratio	1.4 ± 0.4 [1.0 – 2.1], 1.3	2.1 ± 1.3 [0.9 – 4.6], 1.4		1.4 ± 0.4 [1.0 – 2.3], 1.3	2.0 ± 0.7 [1.1 – 2.9], 2.0	2.2 ± 1.4 [0.5 – 4.7], 1.8	
Belgian Malinois (n = 14)	S	7.1 ± 1.7 [5.0 – 10.8], 6.7	4.6 ± 1.1 [2.8 – 6.5], 4.3	95 ± 22 [64 – 135], 94	9.9 ± 3.7 [3.7 – 17.2], 9.8	6.4 ± 3.6 [1.0 – 12.1], 7.1	3.1 ± 2.4 [0.2 – 6.7], 2.9	91 ± 19 [63 – 113], 98
	E	9.3 ± 2.3 [5.7 – 14.9], 9.0	4.6 ± 1.9 [2.1 – 9.4], 4.4		10.5 ± 2.6 [6.5 – 14.7], 10.7	8.4 ± 2.3 [5.2 – 13.2], 8.4	2.7 ± 1.2 [0.5– 4.7], 2.8	
	A	4.8 ± 1.5 [2.4 – 8.0], 4.6	2.2 ± 0.9 [0.8 – 3.5], 2.2		6.2 ± 1.6 [3.4 – 8.6], 6.5	3.5 ± 1.5 [1.3 – 5.4], 3.4	0.9 ± 0.7 [0.3 – 2.5], 0.8	
	E:A ratio	2.2 ± 1.1 [1.1 – 5.1], 1.8	2.5 ± 1.7 [0.9 – 7.8], 2.1		1.8 ± 0.8 [0.9 – 4.0], 1.7	2.9 ± 1.4 [1.0 – 6.1], 3.0	4.0 ± 3.0 [1.3 – 12.7], 3.4	

Results are given as mean ± SD [range], and median.
bpm = Beats per minute.
See Table 2 for remainder of key.

were recorded in late diastole, with the A wave significantly lower than the E and S waves in the 3 segments. A significant correlation was observed between basal, middle, and apical velocities during the cardiac cycle (Table 3). All velocities were also significantly correlated in each segment. No correlation was found between heart rate and A wave in any segment, whereas a positive correlation was detected between heart rate and S wave in the basal and middle segments ($r = 0.25$; $P < 0.05$), but not in the apical segment, and a negative correlation was detected between heart rate and E wave in the basal ($r = –0.25$; $P < 0.05$), middle ($r = –0.22$; $P < 0.05$), and apical ($r = –0.32$; $P = 0.01$) segments. No correlation was found between systolic basal, middle, and apical myocardial velocities and FS.

Associations with breed, age, weight, or sex—No association with sex was detected for any conventional or TDI variable (**Table 5**). Age and body weight were significantly associated with 2 and 3 TDI variables, respectively, particularly in diastole. The association between breed and measurements was pronounced, so we evaluated the breeds represented by the highest number of dogs. This group included Beagles (n = 22; 4.7 ± 2.0 years; 13 ± 3 kg), German Shepherd Dogs (19; 4.0 ± 2.0 years; 35 ± 4 kg), Belgian Malinois (14; 4.6 ± 2.0 years; 30 ± 4 kg), and Golden Retrievers (11; 1.4 ± 0.6 years; 28 ± 5 kg). In these 66 dogs, the association between breed and all systolic longitudinal velocities was most pronounced (Tables 5 and 6).

Discussion

The goal of this study was to determine the velocity patterns of short-axis and long-axis LVFW motion during the cardiac cycle in healthy dogs. A recent study[9] using the same TDI technique and the same observer revealed that both radial and longitudinal left ventricular motion can be quantified in awake dogs with acceptable intraday and interday variability. The results of our study validate use of the TDI technique in dogs and provide information on normal color TDI variables in a healthy canine population. In the present study, 2 views were used to analyze radial and longitudinal LVFW velocities (ie, right parasternal ventricular short-axis view and left apical 4-chamber view, respectively). The analysis may provide useful information on left ventricular function in that LVFW motion is a composite of the movements of different myocardial fibers (ie, circular and longitudinal fibers for radial and longitudinal motion, respectively), and the myocardial fibers may be affected to different degrees in certain pathologic conditions.[7,17,18]

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Whereas determination of mitral annular velocity is used clinically to provide information on overall left ventricular function, use of 2-D color TDI enables assessment of longitudinal ventricular contractility in specific myocardial segments, an advantage which is receiving considerable research interest because impairment of long-axis LVFW contraction and relaxation has been reported in human cardiac disease states (eg, systemic arterial hypertension,[19] ischemic heart diseases,[18] and hypertrophic and dilated cardiomyopathies[20,21]). Moreover, in pathologic conditions such as myocardial ischemia or hypertrophy, the longitudinal LVFW function is impaired before abnormalities in radial motion develop, and assessment via TDI could enhance early diagnosis of myocardial alterations.[7,22,23] Longitudinal myocardial alteration has been reported in a canine model of dilated cardiomyopathy (**Golden Retriever muscular dystrophy [GRMD]**).[24] In that report, young dogs affected by GRMD had low systolic basal and apical velocities and low basal velocity in early diastole, despite an absence of ventricular dilatation or alterations in inotropism. However, the myocardial dysfunction was associated with marked dysfunction of radial endocardial motion, and because of the combined radial and longitudinal alteration, it was not possible to determine which developed first.

In the study reported here, all radial and longitudinal velocity profiles included, after a short isovolumic contraction phase, 1 positive systolic wave (S), and after a short isovolumic relaxation phase, 2 diastolic negative waves (E and A in early and late diastole, respectively). Similar velocity profiles have been described in healthy awake cats.[8] In the feline study, however, summation of the E and A waves was observed in a high percentage of TDI examinations (47% and 64% for the radial and longitudinal examinations, respectively). The fusion of the E waves and A waves was caused by high heart rate (> 220 beats/min) and was not observed in any of the 100 dogs in the present study, probably because the highest heart rate was 171 beats/min.

Our data indicate that different LVFW segments move with different velocities. The endocardial layers move significantly more rapidly than the epicardial layers, and the LVFW velocities decrease significantly from the base to the apex, thus defining radial and longitudinal MVGs, respectively. Compared with instantaneous tissue velocities, which can be affected by the angle of the Doppler interrogation gate and translational cardiac motion, MVGs are used to evaluate regional myocardial function independently of translational motion.[25] In humans, transmural gradients are more reliable and sensitive indicators of regional left ventricular dysfunction than isolated velocity values.[26,27] In the GRMD model of dilated cardiomyopathy, use of TDI permitted identification of the affected puppies early because of the decrease in radial endocardial-epicardial gradient.[e] These new indices of myocardial motion may augment conventional analysis of LV function in animals. Further studies are required to determine the sensitivity and specificity of these indices in canine and feline myocardial diseases.

Although regional myocardial synchrony was not assessed quantitatively in this study, endocardial and epicardial velocity profiles demonstrated similar patterns; the same was observed for the basal and apical velocities, which suggested synchrony between myocardial segments for each LV motion. The present study revealed that, in clinically normal dogs, for a given LVFW motion at a given time, all regional velocities were significantly correlated. Basal, middle, and apical velocities were correlated with each other, and endocardial and epicardial velocities were correlated as well. Furthermore, inside any given myocardial segment, systolic, early, and late diastolic velocities were also significantly correlated. These results indicate that normal LVFW motion in dogs is coordinated. In the present study, the highest LVFW myocardial velocities were recorded in the early diastolic phase of the cardiac cycle, with E waves at least 2 times as fast as A waves in all segments and significantly faster than S waves in all segments except the epicardial and apical segments. This velocity pattern, similar to that observed in healthy humans,[5,26] may be attributable to the fact that during early, but not late, diastole, ventricular myocardial motion is an active process as in systole (ie, an oxygen-consuming process). Moreover, during systole, myocardial motion is countered by opposing forces such as arterial resistance and the aortic valve, whereas this resistance is not present during early diastole. This may explain the higher myocardial velocities in early diastole, compared with systole.[5]

Our results indicate that a positive correlation exists between systolic longitudinal velocities in the basal and middle segments and heart rate. A similar relationship has been reported in healthy cats.[8] The negative correlation between heart rate and early diastolic longitudinal velocities was an unexpected finding because a positive correlation has been reported in cats.[8] This discrepancy between the 2 species is difficult to explain. However, in this population of 100 dogs, heart rate was dependent on the breed, and it is possible that heart rate and canine myocardial velocities are also influenced by breed. In the feline study, only 1 breed of cat (Chartreux cats) was evaluated, whereas 16 canine breeds were evaluated in the present study. In human patients, studies[27] have revealed that the influence of R wave-to-R wave interval on TDI variables is negligible when the patient's body surface area is taken into account.

The present study revealed no relationship between systolic myocardial velocities and fractional shortening. Similar findings were obtained in healthy human subjects, indicating that the correlation between left ventricular ejection fraction and systolic TDI indices is weak.[7] Tissue Doppler imaging studies have revealed progressive decrease in systolic and early diastolic velocities and an increase in late diastolic velocities as age-related changes in healthy human subjects.[7] This suggests a reduction in contractile response and a deterioration in the diastolic motion of the myocardium with aging. Change in myocardial contractility as a function of age was not evaluated in this study because 78% of the studied population was < 5 years old and older dogs were not allocated evenly among breeds. The best strategy for detecting such an effect would be to perform a longitudinal study in the

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same animals. Among the tested effects in the present study, the most substantial was the association of breed with conventional echocardiographic and Doppler variables and TDI variables. The association between breed echocardiographic variables has been published.[28,29] The association between breed and TDI variables is illustrated by the finding that the mean longitudinal velocities of S waves in Belgian Malinois are 1.5 to 3.1 times as high as the values in Beagles. For TDI studies, this effect means that establishing a single reference interval for dogs would be inappropriate.

A slight association with sex was detected in the 4 major breeds evaluated, but not in the overall study population. The association with sex was difficult to interpret because the German Shepherd Dogs, the Belgian Malinois, and all but 2 of the Golden Retrievers were male dogs. A major limitation of our study was that interventricular septal velocities were not recorded in any of the dogs. Therefore, left ventricular synchrony could not be analyzed. Such data would have provided additional information on the assessment of canine left ventricular function by use of TDI. Analysis of myocardial synchrony is important for optimal treatment of specific cardiac diseases, particularly in human patients.[30-33] The other limitation of the present study was that hypothyroidism was not evaluated by use of laboratory testing (serum thyroxine concentration). However, most of the dogs were young adults (ie 78% were < 5 years old) and none had clinical signs of hypothyroidism (weight gain, lethargy, alopecia, and seborrhea). Moreover, none had cardiovascular signs or ECG or echocardiographic abnormalities compatible with hypothyroidism (bradycardia, reduction in amplitude of the P and R waves, first degree atrioventricular block, and left ventricular hypocontractility).

Results of this study indicate that TDI provides rapid and noninvasive assessment of the dynamics of the canine heart by quantifying radial and longitudinal left ventricular velocities in several myocardial segments. This technique provides for measurement of novel indices of myocardial function in dogs. However, because associations between breed and other variables were detected, prospective studies are needed to determine breed-by-breed reference intervals in homogeneous groups of dogs.

a. Dinamap, Critikon Inc, Tampa, Fla.
b. General Electric medical system, Waukesha, Wis.
c. Echo Pac 5.4 software for System 5, GE-Vingmed Ultrasound, Waukesha, Wis.
d. Systat, version 10.0, SPSS Inc, Chicago, Ill.
e. Chetboul V, Escriou C, Blot S, et al. Early detection of regional myocardial function alterations in a dog model of dilated cardiomyopathy by tissue Doppler imaging study (abstr). *Circulation* 2001;104(suppl):351.

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