Characterization of systolic intervals in healthy, conscious sheep

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Objective—To characterize systolic intervals of the left ventricle and their relationship with heart rate in conscious sheep.

Animals—11 healthy Romanov sheep (age range, 3 months to 10 years).

Procedures—Systolic intervals and indices of myocardial contractility of the left ventricle were measured in conscious sheep by use of polycardiography.

Results—The mean ± SD pre-ejection period was 59 ± 12 milliseconds, and the mean left ventricular ejection time was 194 ± 34 milliseconds. The mean myocardial tension index was 0.22 ± 0.05, and the mean ratio of the pre-ejection period to ejection time was 0.30 ± 0.09. Total electromechanical stoke, mechanical stoke, and ejection time varied inversely with heart rate. The electromechanical delay and pre-ejection period were not correlated with heart rate, nor were the myocardial tension index and the ratio of the pre-ejection period to ejection time. The isovolumetric contraction index and isovolumetric contraction time were not significantly correlated with heart rate, although the values for the correlation coefficient were moderate ($r = -0.561$ and $r = -0.482$, respectively).

Conclusions and Clinical Relevance—Although a larger study would be needed to provide reference intervals for healthy sheep, the results of the study reported here provided useful information for the cardiac evaluation of sheep. (Am J Vet Res 2009;70:330-333)

Measurement of systolic intervals is a useful tool for evaluation of cardiac performance. Systolic intervals can be evaluated by use of echocardiography, various modes of polycardiography, and other techniques. Polycardiography is a noninvasive and specific technique that can be used in nonanesthetized mammals. This particular method is valuable for accurate evaluation of cardiac performance because myocardial contractility is influenced by anesthetics. More information is needed to improve estimates of cardiac performance in veterinary medicine. In sheep, only incomplete data concerning systolic intervals and heart rate are available. The purpose of the study reported here was to measure systolic intervals for the left ventricle of conscious, healthy sheep with attention to variations in heart rate.

Materials and Methods

Animals—Six female and 5 male Romanov sheep were included in the study. Ages ranged from 3 months to 10 years, including 3 juvenile (3 to 4 months), 4 mature (1 to 3 years), and 4 older (8 to 10 years) sheep. The study protocol was reviewed and approved by an institutional animal studies committee.

Polycardiographic evaluation—Each sheep was restrained in right lateral recumbency without sedation. Polycardiograms were obtained by means of a computer system that had a speed of 200 mm/s and an accuracy of 24 bits (Figure 1). The polycardiogram consisted of a standard bipolar lead ECG, phonocardiogram, and apexcardiogram that were recorded synchronously for 30 seconds. The ECG channel of the polygraph had a bandwidth and sampling rate of 0.5 to 75 Hz and 1,000 Hz, respectively.

To obtain a bipolar limb lead ECG, needle electrodes were attached to the skin of the proximal aspect of each hind limb and forelimb. Three standard limb leads (I, II, and III) were used. For lead I, the negative component was a yellow electrode and the positive component was a red electrode. For lead II, the negative component was a red electrode and the positive component was a green electrode. For lead III...

Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>ET</td>
<td>Ejection time</td>
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<tr>
<td>ICT</td>
<td>Isovolumetric contraction time</td>
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<td>LV</td>
<td>Left ventricular</td>
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<tr>
<td>PEP</td>
<td>Pre-ejection period</td>
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<tr>
<td>QS₂</td>
<td>Interval from the onset of the QRS complex to the second heart sound</td>
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<td>S₁S₂</td>
<td>Interval from the first heart sound to the second heart sound</td>
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Heart rate was determined from measurement of the R-R interval in the lead II ECG. The duration of electromechanical systole (QS₁) was measured from the onset of the QRS complex in the lead II ECG to the first high deflection (the mitral valve deflection) of the first heart sound in the phonocardiogram. The duration of mechanical systole (S₂S₅) was measured from the initial high-frequency component of the first heart sound (the mitral valve deflection) to the initial high-frequency component of the second heart sound in the phonocardiogram. The ET was measured from the ejection peak indicated on the apexcardiogram to the initial high-frequency component of the second heart sound. The ICT was calculated by subtracting ET from QS₅, and the PEP was obtained by subtracting ET from QS₂.

On the basis of the aforementioned measurements, indices of ventricular contractility were defined. The myocardial tension index was calculated as PEP/QS₂.¹⁶ The intrasystolic index was defined as ET/S₂S₅. The isovolumetric contraction index and the systolic time index were computed as ICT/PEP²⁴ and ICT/ET,²⁵ respectively. The PEP-to-ET ratio, which is a commonly used index of contractility and performance of the left ventricle, was determined. The duration of cardiac output ejection was defined as a product of ET and heart rate.

Two 30-second polycardiograms were acquired for the period of 5 to 10 minutes in all sheep. Afterward, the better record (invariably the second polycardiogram) was chosen for subsequent analysis.

Statistical analysis—All values for each sheep were averaged on the basis of measurements from 5 representative cardiac cycles that were selected from the better polycardiogram. Linear regression equations and correlation coefficients (r) were calculated for the relationship between heart rate and systolic intervals. Data are presented as mean ± SD.

Results

Sinus rhythm was detected in all sheep examined. The values of systolic intervals and indices of myocardial contractility were summarized (Table 1). Proportions of various phases of the cardiac cycle were represented as follows: electromechanical delay, 7%; ICT, 5%; PEP, 12%; ET, 41%; and S₂S₅, 47%.

Statistical analysis revealed that QS₁, S₂S₅, and ET were strongly and inversely correlated with heart rate (r = −0.834 [P = 0.001], r = −0.887 [P < 0.001], and r = −0.828 [P = 0.006], respectively). These systolic intervals varied with respect to heart rate according to the following regression equations:

\[
QS_1 = 414.6 - 1.2X \text{ heart rate}
\]

\[
S_2S_5 = 382.8 - 1.22X \text{ heart rate}
\]

\[
ET = 341.2 - 1.11X \text{ heart rate}
\]
The ICT varied inversely with heart rate according to the regression equation $ICT = 47.66 - 0.17 \times HR$, and the correlation coefficient ($-0.482$) was not significant. The electromechanical delay and ICT were not correlated with heart rate ($r = 0.043$ and $r = -0.282$, respectively).

The isovolumetric contraction index was not significantly correlated with heart rate, although the value for the correlation coefficient was moderate ($r = -0.561$). The regression equation was as follows: isovolumetric contraction index $= 0.645 - 0.002 \times HR$. There was an insignificant correlation between the myocardial tension index and heart rate ($r = 0.284$) and between the PEP-to-ET ratio and heart rate ($r = 0.281$). Other indices of myocardial contractility were also uncorrelated with heart rate as follows: systolic time index, $r = -0.092$; and intrasystolic index, $r = 0.069$.

### Discussion

In the study reported here, systolic intervals were measured noninvasively in conscious, healthy sheep. When the dependence of PEP, ET, and PEP-to-ET ratio on heart rate was taken into account, the values of these systolic intervals were in consistent agreement with other findings in fetal lambs\(^8\) and newborn and adult sheep.\(^1,3,10\) The proportion of the cardiac cycle that constitutes the ICT in sheep is similar to that in fetal lambs.\(^10\) The mean value of the ICT reported for our study was less than that of another study,\(^19\) in which ICT was defined from the aortic and LV pressure curves. In addition, our data differed from values reported for electrical delay and ICT in individual sheep in another study.\(^4\)

The correlations between systolic intervals ($QS$, $S_s$, and ET) and heart rate in our study were comparable with those reported for sheep by other researchers.\(^8\) However, compared with the results of our study, the correlation between ICT and heart rate reported for the other study\(^8\) was lower ($r = -0.170$). This difference between study results is likely attributable to differing experimental conditions because the other study involved a protocol that included a range of heart rates obtained by means of pharmacologic interventions and electrical pacing.

The myocardial tension index, which reflects the time a heart needs to prepare for blood ejection (ie, unproductive expenditure of contraction time),\(^16\) is a reliable index of ventricular contractility that can be measured by means of noninvasive techniques. The myocardial tension index decreases when systolic function improves. The PEP-to-ET ratio is a commonly used means of assessing ventricular performance,\(^2,3,7-11,14,15,17,18\) that decreases when systolic function improves. Reduced ventricular contractility is reflected by an increase in the PEP-to-ET ratio. In comparison to other domestic ungulates (eg, horse or swine), sheep have intermediate values for the PEP-to-ET ratio. Horses have a mean value of 0.131 to 0.138,\(^3\) whereas swine have a mean value of 0.47.\(^7\) The variety in PEP-to-ET ratios among domestic ungulates may be attributable to differing requirements for physical endurance. The correlation between the PEP-to-ET ratio and heart rate in our study is comparable with that reported for sheep by other researchers.\(^8\)

In the present study, systolic intervals in sheep were measured via synchronous recording of a standard bipolar limb lead ECG, phonocardiogram, and apexcardiogram. Each recording provides the data by which systolic intervals can be measured. The onset of the ECG QRS complex is the beginning of total electromechanical systole of the ventricles. The onset of the systolic upstroke of the apexcardiogram coincides with the beginning of the pressure rise within the left ventricle,\(^18,22-23\) and, therefore, with the end of the electromechanical delay and the beginning of isovolumetric contraction. However, there is typically little scatter between the beginning of the LV pressure rise and the onset of the systolic upstroke of the apexcardiogram,\(^22,23\) which is not always obtainable.\(^22\) Although the initial high-frequency component of the first heart sound (the mitral valve deflection) does not correspond to but follows the beginning of the LV pressure rise,\(^24\) it is precisely related to completion of mitral valve closure as manifested in the echocardiogram\(^25\) and is used for noninvasive measurements of systolic intervals, particularly measurement of the end of the electromechanical delay.\(^6,7\) In the present study, the mitral deflection in the phonocardiogram was selected as designating the end of the electromechanical delay. However, because the mitral valve remains open for approximately 75% of isovolumetric contraction,\(^16\) our choice may have slightly overestimated the value of the electromechanical delay.

The initial high-frequency component of the second heart sound in the phonocardiogram, used in our study as the end point of the ejection period, corresponds to aortic valve closure,\(^24\) although it does not originate from the coaptation of the aortic valve cusps per se and is related to events that occur at the time of or slightly after coaptation of the aortic valve cusps.\(^26\) A fixed temporal relationship between the apexcardiogram or phonocardiogram and aortic valve cusps opening, which begins before ejection of blood,\(^27,28\) does not exist. We had no opportunity to exactly determine the onset of ejection of blood into the aorta via echocardiography, although we used the ejection peak of the apexcardiogram, which occurs in association with ejection of blood into the aorta,\(^21\) for this purpose. The ejection point is not

### Table 1—Systolic intervals and indices of myocardial contractility in 11 healthy sheep.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
<th>Range</th>
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<tbody>
<tr>
<td>Duration of cardiac cycle (ms)</td>
<td>479 ± 106</td>
<td>367–665</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>133 ± 26</td>
<td>91–183</td>
</tr>
<tr>
<td>Duration of QRS complex (ms)</td>
<td>45 ± 3</td>
<td>40–49</td>
</tr>
<tr>
<td>QT interval (ms)</td>
<td>257 ± 31</td>
<td>224–320</td>
</tr>
<tr>
<td>Electromechanical delay (ms)</td>
<td>34 ± 6</td>
<td>26–45</td>
</tr>
<tr>
<td>ICT (ms)</td>
<td>25 ± 9</td>
<td>11–41</td>
</tr>
<tr>
<td>PEP (ms)</td>
<td>59 ± 12</td>
<td>37–77</td>
</tr>
<tr>
<td>ET (ms)</td>
<td>194 ± 34</td>
<td>157–263</td>
</tr>
<tr>
<td>$S_s$ (ms)</td>
<td>220 ± 35</td>
<td>181–291</td>
</tr>
<tr>
<td>$D_s$ (ms)</td>
<td>254 ± 37</td>
<td>214–330</td>
</tr>
<tr>
<td>Myocardial tension index</td>
<td>0.23 ± 0.04</td>
<td>0.16–0.29</td>
</tr>
<tr>
<td>PEP-to-ET ratio</td>
<td>0.31 ± 0.08</td>
<td>0.20–0.44</td>
</tr>
<tr>
<td>Intrasystolic index</td>
<td>0.88 ± 0.05</td>
<td>0.78–0.94</td>
</tr>
<tr>
<td>Isovolumetric contraction index</td>
<td>0.42 ± 0.08</td>
<td>0.30–0.53</td>
</tr>
<tr>
<td>Systolic time index</td>
<td>0.13 ± 0.05</td>
<td>0.06–0.23</td>
</tr>
<tr>
<td>Duration of cardiac ejection (ms)</td>
<td>25 ± 3</td>
<td>22–30</td>
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always demarcated on an apexcardiogram and often varies significantly from the true point of onset of LV ejection; rather, it tends to follow the calculated ejection point and the crossing point of the LV and aortic pressure curves. However, ejection of blood into the aorta is accompanied by ejection sounds. The ejection sound of aortic origin coincides with the onset of pressure rise in the aortic root and achievement of a fully opened aortic valve. This aortic ejection sound is manifested as the aortic ejection component of a typical first heart sound and starts after the mitral component of the LV phonocardiogram. In our investigation, the apexcardiographic ejection peak, determined unequivocally as the highest sharp apexcardiographic peak, occurred during the second half of the first heart sound.

Another reason for choosing the ejection peak of the apexcardiogram as the beginning of blood ejection in our noninvasive measurements was that the apexcardiogram reflects changes in LV configuration associated with contraction and relaxation. The systolic upstroke of the apexcardiogram coincides with the sharp upstroke of the LV pressure curve and represents LV isovolumetric contraction. At the end of isovolumetric contraction, maximal long-axis lengthening of the left ventricle is typically evident. One might assume, therefore, that this maximal lengthening, at least in clinically normal hearts, corresponds to the highest point in the apexcardiogram (ie, the ejection peak); however, additional research is required to confirm this assumption in sheep.

The present study included a small number of sheep of a wide age range, but investigating the effect of age on systolic intervals was not our objective. Instead, we attempted to determine the range of systolic intervals in conscious sheep, irrespective of age, and included sheep from various age groups to minimize the influence of age on the range of systolic intervals measured. The systolic intervals and indices of myocardial contractility of the left ventricle measured in the present study pertained to conscious, healthy sheep with heart rates in the range of 91 to 163 beats/min.

References