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Electrocardiographic Monitoring in the Göttingen Minipig

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The purpose of the study reported here was to determine conditions for electrocardiographic monitoring in the Göttingen minipig in view of its use as a second non-rodent species in toxicology studies. Electrocardiograms were recorded from conscious minipigs (6/sex) maintained in a sling. The three standard bipolar limb leads (I, II, III), the three augmented unipolar limb leads (aV_R, aV_L, aV_F), the triangular Nehb-Spöri leads (dorsal, axial, ventral) and their corresponding unipolar leads were recorded, and automated analysis of amplitudes and intervals was made.

Major QRS patterns were not observed for any of the bipolar and unipolar leads. For triangular leads, the amplitude of waves was higher than that for limb leads, and the rS pattern dominated for dorsal, axial ventral and aV_F-Ventral leads. The qR pattern dominated in the aV_R-dorsal lead, whereas consistency and dominant patterns were not observed for the aV_L-axial lead. For limb leads, the position of the electrode affected the ECG. Electrodes placed on the cubital and stifle joints were the preferred positions since the P- and R-waves were clearly identifiable with amplitudes > 0.2 mV. Also, the T-wave amplitude was (positive or negative) > 0.2 mV in at least two leads, making the determination of the QT-interval accurate. For the triangular leads, the position of the electrode had less influence on the amplitude of deflections. However, if the axial lead is to be used for calculation of intervals and amplitudes, the xyphoid process is the preferred position. In conclusion, the triangular lead system is recommended for recording ECGs in minipigs. Limb leads could be used in connection. The cubital and stifle joints for standard limb leads and the neck, sacrum, and xyphoid process for triangular leads are the preferred positions for electrodes.

The minipig is becoming an attractive model in toxicology studies, as judged by the number of symposia, working groups, and publications (1, 2). The pig has many physiologic similarities with humans, especially in cardiovascular structure and function. For this reason, electrocardiographic determination in this species is of interest.

Electrocardiographic recording in conventional and miniature swine has been described by several authors (3-7). Generally, only the standard limb leads and the V_{10} (CV10, electrode over the seventh dorsal spinous process) lead have been used. In most reports, the position of the electrodes was not described.

Dukes and Szabuniewicz (4) described the variability of the QRS complex in conventional and miniature swine of various ages, using the standard leads (I, II, III, aV_R, aV_L, aV_F, and V10) where electrodes were affixed behind the point of the shoulder in the forelimb and the point of the stifle joint in hind limbs.

Dubois (8) concluded that use of limb leads for ECG recording in swine does not produce an accurate representation of the electrical activity of the heart and use of such leads produces erroneous results, which is in agreement with the basic theory of electrocardiography. The author validated and recommended a lead system in which electrodes were placed on the cranial edge of the scapula and the retro-xyphoid zone. In this system, the heart is the center of a projection area and its plane, through which passes the sagittal axis of the heart. Detweiler (9-11) reported that, in the hoofed mammals, and therefore minipigs, the QRS vectors are generally directed from the sternum toward the spine. The QRS in these animals is negative, and therefore, conventional leads (I, II, III) are not suitable for recording the ECG. He reported use of similar, triangular leads for farm animals and laboratory rats and described the dorsal, axial, and ventral leads. The reasons for the inadequacy of limb leads are in part linked to anatomic differences between species. In pigs the thoracic topography of the heart is different from that of the dog. The projection of the heart is between the second and fifth intercostal spaces, and the apex is projected toward the cartilage of the sixth rib. In dogs, the heart projection is between the third and sixth intercostal spaces and the apex is projected toward the cartilage of the seventh rib. In pigs, the right ventricle forms a sharp angle with the sternum, whereas in dogs, it is parallel to the sternum. In humans, the heart is oblique, about three-quarters of it is to the left of the medial plane; the apex is projected toward the lateral part of the fifth left interchondral space, and the base of the heart is projected under the right-sided border of the sternum and the third to fifth rib cartilages (12).

The size of deflections recorded on the ECG is dependent on the distance between the electrodes of the leads and the heart. The size of the deflection is a square function of the distance, so that small changes in distances can make large changes in the amplitude of deflections (13).

In the past five years, there were only two published reports on ECG recordings in miniature swine and only one of them involved use of the triangular leads in Göttingen minipigs (6, 7). In addition, none of the published reports have involved automated ECG analysis in swine. The purpose of the study reported here

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Table 1. Position of the electrodes

Electrode	Limb leads		Triangular leads	
	Position 1	Position 2	Position 1	Position 2
RA (red)	Cubital joint	Cranial edge of shoulder half distance on the scapula	Neck, behind ear	Neck, behind ear
LA (yellow)	Cubital joint	Cranial edge of shoulder half distance on the scapula	Sacrum	Sacrum
Neutral (black)	Stifle	Thigh	Right thigh	Right thigh
LF (green)	Stifle	Thigh	Xyphoid process	Sternal manubrium

was to establish standard procedures for recording and analyzing the ECG in Göttingen minipigs and to describe the ECG patterns in this animal.

Materials and Methods

Animals and housing conditions. Göttingen minipigs (6 males and 6 females) were obtained from Ellegaard Göttingen minipigs Aps (Dalmose, Denmark) and were housed in our facility for four months. At the start of the study (day 1), pigs were five to five and a half months old, with mean ± SD body weight of 8.5 ± 0.5 kg for males and 8.0 ± 0.3 kg for females.

Animals were housed individually in large pens allowing visual, olfactory, and tactile contact with animals in the adjacent neighboring pens. Room temperature and humidity were maintained at 24 ± 2°C and 60 ± 20% relative humidity, respectively. The HEPA-filtered air was changed 14 times/h, and artificial lighting was provided from 7 a.m. to 7 p.m. Food (UAR, Villemoisson-sur-Orge, France; certified pellets or SDS diet obtained from the animal supplier) was provided in two daily rations.

Electrocardiographic recordings. Electrocardiograms were recorded from conscious animals maintained in a sling, a procedure to which they were accustomed. The three standard bipolar limb leads (I, II, III), the three augmented unipolar limb leads (aV_R, aV_L, aV_F), the triangular Nehb-Spöri leads (dorsal, axial, ventral) and their corresponding unipolar leads were recorded, using a Cardiostat at a paper speed of 50 mm/sec and sensitivity of 10 mm/1 mV (frequency of response 0.05 to 100 Hz). Simultaneously, the analog outputs were fed into the acquisition software. For each recording, data were acquired during 20 sec, simultaneously on three leads, using IOX software (Emka Technologies, Paris, France), with a sampling rate set at 500 Hz. Analysis of the ECG was performed in a second stage, using ECG-AUTO software (Emka Technologies) to process data files produced by the IOX software. The basic principle of ECG-AUTO is to use shape recognition algorithms to evaluate whether the analyzed signal is sufficiently close to one of the waveforms stored in a library of reference ECG complexes. Waveform libraries can be built and edited by the user.

The software provided amplitudes and intervals for a wide range of ECG components. The QRS patterns were determined from the paper ECG produced by the Cardiostat, and were classified as were those described for dogs by Tilley (14).

Electrode positions. Subcutaneous needle electrodes were used for each lead system. For limb leads, electrodes were placed on the cubital and stifle joints; for triangular leads, they were placed on the neck, xyphoid, and sacrum. This position was referred to thereafter as "position 1". To study the effects of the electrodes' position on electrocardiographic parameters, an additional position was added for each lead system (limb and triangular leads) and referred to as "position 2". The anatomic references for each electrode and position are described in Table 1 and Fig. 1.

Statistical analysis. Data for males and females were compared graphically, using the 95% confidence interval. Comparison between positions of the electrodes was performed, using the student *t* test for paired data. Significance was set at 5%.

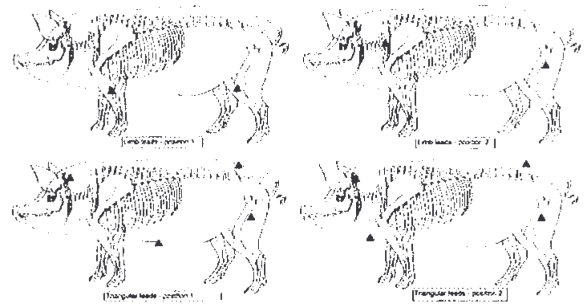

Figure 1. Schematic representation of the position of the electrodes (dark triangles) for ECG recording of limb and triangular leads.

Ethical considerations. The protocol for this study was approved by the Pfizer Amboise ethics committee. All technicians involved in this work were qualified and well trained to perform routine procedures and electrocardiographic recordings in minipigs.

Results

Examples of the ECG from the bipolar, triangular, and corresponding unipolar leads are seen in Fig. 2 and Fig. 3.

Heart rate and rhythm. There were no apparent differences between sexes; therefore, data were combined. Individual heart rate values were in the range of 90 to125 beats/min (Table 2). The rhythm was regular sinus rhythm, and there was no obvious effect of respiration. The maximal RR interval (RR_{maxi}) to the median RR interval (RR_{med}) ratio was in the range of 1 to1.4 (Table 2).

The P-wave and PR interval. In limb leads (I, II, III), unipolar leads aV_L and aV_F, dorsal, axial, and aV_F-ventral leads, the P-wave was always positive. In the unipolar aV_R and aV_R-dorsal leads, it was always negative. In the ventral lead, it was absent, positive, or negative in seven, three, and two of 12 pigs, respectively. When the P-wave was positive, its amplitude was higher in triangular leads than in limb leads (Table 3).

The QRS patterns (Table 4). In limb leads (I, II, III), given the small amplitude of waves, the patterns of the QRS complex were subjected to large variations and it was difficult to distinguish between the following patterns: QRs, qR, Rs, R-Rs, RS-RS, and rS. Major patterns were not observed for any of the bipolar and unipolar leads.

In triangular leads, the amplitude of waves was higher than that in limb leads; therefore, there were no difficulties in determining the QRS patterns. The rS pattern dominated in dorsal, axial ventral, and aV_F-ventral leads. The qR pattern dominated

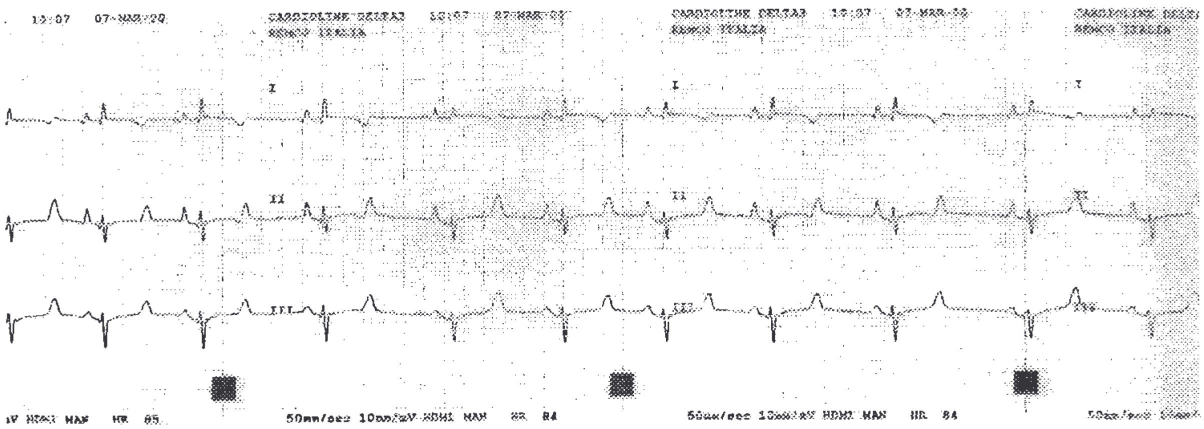

Figure 2. Limb lead ECG recorded from a minipig. The electrodes were placed on the cubital and stifle joints. Leads I, II, and III are standard limb lead I, II, and III, respectively.

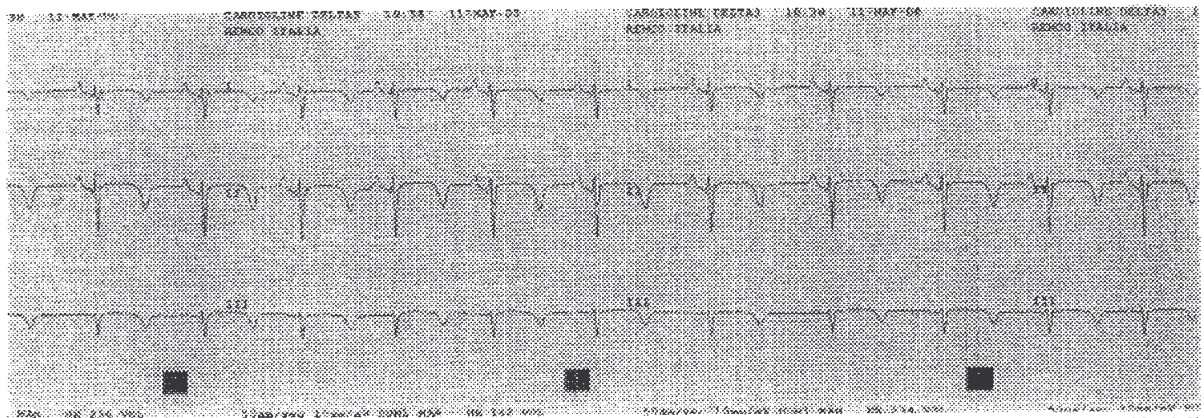

Figure 3. Triangular lead ECG recorded from a minipig. The electrodes were placed on the neck, sacrum, and xyphoid process. I = dorsal lead, II = axial lead, III = ventral lead.

Table 2. Heart rate, RR interval and RR_{max}-to-RR_{med} ratio in male and female minipigs (n = 12)

Lead system	Heart rate (beats/min)	RR interval (msec)	RR_{max}/RR_{med}
Limb lead II			
Mean ± SD	102.7 ± 8.0	527.3 ± 40	1.2 ± 0.1
Minimum	91.3	498.0	1.1
Maximum	120.5	630.2	1.4
Triangular-axial lead			
Mean ± SD	106.4 ± 12	566.1 ± 60.5	1.2 ± 0.1
Minimum	90.9	474.9	1.0
Maximum	125.8	640.3	1.4

in aV_R-dorsal, whereas consistency and dominant patterns were not observed in aV_L-axial lead.

The QRS intervals and amplitudes (Table 5). For any of the leads, when the Q-wave was present, its amplitude did not exceed −0.3 mV except for the aV_R-dorsal lead where it reached −0.8 mV.

For limb leads, the highest R-wave amplitude was obtained in lead I > II > III and was in inverse order for the unipolar leads aV_F > aV_L > aV_R. Maximal individual values did not exceed 0.93 mV. For triangular leads, the highest amplitude was obtained with aV_R-dorsal lead > axial; there were no differences between dorsal, ventral, aV_L-axial, or aV_F-ventral leads.

The S-wave amplitude was similar for all limb leads, with the highest value being 0.79 mV. For triangular leads, the amplitude of the S-wave was higher than that for limb leads, with highest values observed for the axial = aV_F-ventral > ventral > dorsal > aV_L-axial. For the aV_R-dorsal lead, the S-wave was absent, which is consistent with the QRS patterns.

The T-wave was labile (positive, negative, biphasic, or null) for all leads (Table 6). When it was negative, there were no differences between limb and triangular leads. When it was positive, its amplitude was generally higher for triangular than for limb leads (Table 7). The ST segment and QT intervals are shown in Table 8. There were no differences between leads.

Electrocardiographic abnormalities. Ventricular premature complexes occurred sporadically in two pigs (Fig. 4).

Effects of the position of the electrode on ECG parameters. When assessing the effects of position of the electrodes on wave forms, we focused on standard limb leads (I, II, III) and by analogy, the standard triangular leads (dorsal, axial, ventral). We decided that, for a particular lead system, a position has the advantage over another when, for two of the three leads, the

Table 3. The P-wave parameters recorded from male and female minipigs (n = 12). Electrodes were placed on the cubital and stifle joints for standard limb leads and on the neck, sacrum, and xyphoid process for triangular leads

	Lead											
Variable	I	II	III	aV_R	aV_L	aV_F	Dorsal	Axial	Ventral	aV_R-dorsal	aV_L-axial	aV_F-ventral
P-Amplitude (mV)												
Mean	0.19	0.24	0.07	-0.20	0.14	0.15	0.27	0.27	0.00	-0.26	0.12	0.14
SD	0.06	0.06	0.04	0.07	0.04	0.05	0.07	0.07	0.03	0.07	0.04	0.04
Minimum	0.09	0.18	0.02	-0.36	0.07	0.09	0.15	0.17	-0.03	-0.37	0.07	0.08
Maximun	0.32	0.35	0.14	-0.15	0.22	0.23	0.37	0.40	0.05	-0.17	0.18	0.22
P-Duration (msec)												
Mean	42.1	44.1	46.9	55.2	55.3	44.6	42.3	40.3	46.7	51.7	50.8	46.4
SD	9.0	4.9	8.5	8.1	4.6	5.6	5.6	7.2	7.0	5.8	4.7	9.4
Minimum	31.0	36.7	32.0	38.1	47.2	35.0	30.3	27.8	33.5	38.0	43.9	33.9
Maximum	63.4	51.7	61.2	63.3	60.7	55.4	51.3	52.3	56.5	60.1	59.8	60.0
P-Area												
Mean	2.7	4.6	1.7	-2.8	2.5	3.2	5.4	6.0	0.9	-5.7	2.1	3.1
SD	1.1	1.4	1.0	0.9	1.1	1.2	1.5	1.8	0.6	1.5	0.7	1.1
Minimum	1.1	3.1	0.0	-4.9	1.2	1.7	2.7	3.6	-0.3	-8.8	1.0	1.7
Maximum	4.1	8.3	3.4	-1.8	5.4	5.5	8.3	9.8	2.1	-3.3	3.2	5.8
PR-Interval (msec)												
Mean	90.4	83.6	86.2	97.2	93.5	83.7	79.0	84.3	81.9	90.1	83.1	92.6
SD	14.8	7.7	7.2	10.5	11.1	8.0	7.1	13.0	26.2	8.8	6.6	6.1
Minimum	71.9	70.4	71.7	80.8	76.5	69.6	68.0	67.6	0.0	74.1	74.5	80.2
Maximum	122.0	95.7	96.0	111.0	110.4	94.5	91.2	111.2	96.8	100.8	94.6	101.4

Table 4. Incidence of QRS patterns in ECGs recorded from male and female minipigs (n = 12). In position 1, electrodes were placed on the cubital and stifle joints for standard and unipolar limb leads (I, II, III, aV_R, aV_L, aV_F), and on the neck, sacrum, and xyphoid process for triangular leads and the corresponding unipolar leads (dorsal, axial, ventral, aV_R-dorsal, aV_L-axial, aV_F-ventral). In position 2, electrodes were placed on the cranial edge of the scapula and thigh for standard limb leads and on the neck, sacrum, and sternal manubrial process for triangular leads

		Lead												
	Position	qRs	qR	QR	QS	R	Rs	RS	rS	rsR'	rSR'	rSr'	Rsr'	ND
I	1	3	6		1			2						
	2		6	1		1	1	1						2
II	1	4			1			5	2					
	2							1	11					
III	1							2	7			1	2	
	2								12					
aV_R	1			2		1			2		1	1	5	
	2		5	4		2				1				
aV_L	1	2	7	1			1							1
	2		12											
AV_F	1				1	1		6	4					
	2							1	11					
Dorsal	1								12					
	2							2	10					
Axial	1								12					
	2				2				9					1
Ventral	1								12					
	2		2	3		1			4		1	1		
aV_R-dorsal	1		12											
	2		12											
aV_L-axial	1	2	5		1		1	1	1				1	
	2	2			1		2	3	4					
aV_F-ventral	1								12					
	2		1	2	1		1		5	1				1

ND = Not determined.

amplitude was the greatest. As expected, changing the position of the electrode with any of the leads did not affect electrocardiographic intervals (P-duration and RR, PR, QRS, QT, and ST intervals).

For limb lead II, there were no differences in the amplitude of the P-wave between either position. For lead I, the P-wave amplitude was significantly lower for position 2 (electrodes on the scapulae) and significantly higher for the same position for lead III. For triangular leads, there were no differences between either position for the dorsal lead. For the axial lead, the P-wave amplitude was significantly lower for position 2 (electrodes on the sternal manubrium) and significantly higher for the same position for the ventral lead (Fig. 5).

For limb leads, position 2 produced more consistent QRS patterns for leads II and III than did position 1; however, it did not change considerably the patterns for lead I (Table 4). For triangular leads, the most consistent QRS patterns were obtained for position 1. For both lead systems, advantage of one position over the other was not observed for the Q-wave amplitude.

For limb leads I and II, the R-wave was significantly lower for position 2 and significantly higher for lead III in the same position. For triangular leads, differences were not observed for the dorsal and ventral leads whereas the R-wave was significantly lower for position 2 for the axial lead. (Fig. 6). For limb leads II and III, position 2 produced significantly greater S-wave than did position 1. For the three triangular leads, position 1 produced greater S-waves than did position 2 (Fig. 7).

Changing the position of the electrode did not affect consider-

Table 5. QRS complex recorded from male and female minipigs (n = 12). Electrodes were placed on the cubital and stifle joints for standard limb leads and on the neck, sacrum and xyphoid process for triangular leads

	Lead											
Variable	I	II	III	aV_R	aV_L	aV_F	Dorsal	Axial	Ventral	aV_R-dorsal	aV_L-axial	aV_F-ventral
Q-amplitude (mV)												
Mean	-0.09	-0.10	-0.07	-0.01	-0.10	-0.08	-0.12	-0.17	NW	-0.35	-0.09	NW
SD	0.04	0.04	0.03	0.04	0.04	0.03	0.04	0.06	NW	0.20	0.06	NW
Min	-0.16	-0.19	-0.14	-0.14	-0.16	-0.13	-0.22	-0.30	0.00	-0.80	-0.23	0.00
Max	-0.02	-0.03	-0.03	0.00	-0.06	-0.05	-0.07	-0.06	0.00	-0.15	-0.04	0.00
R-amplitude												
Mean	0.39	0.33	0.18	0.14	0.21	0.22	0.26	0.44	0.25	1.17	0.30	0.29
SD	0.23	0.23	0.14	0.10	0.17	0.17	0.17	0.27	0.15	0.31	0.15	0.14
Min	0.01	0.10	0.03	0.08	0.03	0.01	0.05	0.09	0.09	0.74	0.07	0.07
Max	0.85	0.93	0.48	0.40	0.61	0.65	0.66	1.07	0.64	1.76	0.62	0.49
S-amplitude (mV)												
Mean	-0.10	-0.31	-0.45	-0.29	-0.33	-0.33	-0.79	-1.65	-0.92	NW	-0.13	-1.28
SD	0.11	0.21	0.21	0.23	0.21	0.21	0.22	0.40	0.38	NW	0.08	0.45
Min	-0.32	-0.79	-0.79	-0.77	-0.73	-0.74	-1.12	-2.26	-1.60	0.00	-0.25	-2.32
Max	0.00	-0.04	-0.23	0.00	-0.07	-0.05	-0.43	-1.12	-0.39	0	-0.05	-0.73
QRS-duration (msec)												
Mean	51.1	51.4	52.9	46.1	47.8	52.0	52.2	53.7	50.6	51.5	49.4	52.0
SD	5.4	3.1	2.7	5.1	3.5	2.7	2.1	2.8	5.5	4.9	5.4	5.5
Min	41.6	47.0	48.4	40.2	42.4	46.7	48.7	49.2	44.4	44.6	41.8	46.2
Max	57.9	56.2	56.5	58.3	52.6	56.6	56.9	57.5	63.9	57.6	59.5	66.1
QRS-area												
Mean	3.5	-1.5	-4.9	-1.3	-3.1	-1.9	-10.1	-22.6	-11.7	16.0	2.1	-17.6
SD	4.1	5.1	2.9	4.7	3.6	2.7	3.6	6.3	5.5	5.1	2.6	7.1
Min	-5.2	-14.6	-10.8	-6.1	-10.6	-7.9	-16.5	-33.2	-19.1	9.9	-2.6	-31.5
Max	8.1	4.4	-1.7	10.6	1.9	2.3	-5.3	-14.4	-4.2	24.7	5.0	-9.4

NW = No wave detected.

Table 6. T-wave polarity in ECGs recorded from male and female minipigs (n = 12). In position 1, electrodes were placed on the cubital and stifle joints for standard and unipolar limb leads (I,II,II, aV_R, aV_L, aV_F), and on the neck, sacrum and xyphoid process for triangular and corresponding unipolar leads (dorsal, axial, ventral, aV_R-dorsal, aV_L-axial, aV_F-ventral). In position 2, electrodes were placed on the cranial edge of the scapula and thigh for standard limb leads and on the neck, sacrum and sternal manubrial process for triangular leads

Lead		Position 1	Position 2
I	Biphasic	2	3
	Negative	7	5
	Positive	2	2
II	Biphasic	3	3
	Negative	3	3
	Positive	6	6
III	Biphasic		5
	Negative	3	1
	Positive	9	6
aV_R	Biphasic	4	2
	Negative	2	3
	Positive	4	7
aV_L	Biphasic		2
	Negative	3	6
	Positive	7	4
aV_F	Biphasic	2	2
	Negative	5	6
	Positive	5	4
Dorsal	Biphasic	2	1
	Negative	5	3
	Positive	5	8
Axial	Biphasic	2	1
	Negative	5	
	Positive	4	10
Ventral	Biphasic	2	1
	Negative	3	4
	Positive	6	4
aV_R-dorsal	Biphasic		2
	Negative	5	6
	Positive	7	4
aV_L-axial	Biphasic	3	
	Negative	5	8
	Positive	2	3
AV_F-ventral	Biphasic		1
	Negative	7	
	Positive	4	8

ably the T-wave polarity (Table 6). For the three standard limb leads, position 1 produced the greatest positive or negative T-waves. For triangular leads, position 2 produced the highest positive and negative T-wave. However, due to the lability of the T-wave and the large individual variations we concluded that the position has no effect on the amplitude of the T-wave.

Discussion

When interpreting ECGs, the general practice is to use multichannel recorders. This enables recording of at least three leads simultaneously and, therefore, allows detection or confirmation of abnormalities seen in any of the leads. Also, the waves should be clearly detectable in at least two of the leads. When using manual calculations, the accuracy of measurements is 0.5 to 1 box or mm, which in terms of amplitude is 0.05 to 0.1 mV. Therefore, any wave < 0.1 mV is difficult to characterize. We applied this rationale for interpretation of our results.

It has been documented that the position of the limbs influences the ECG in the standard lead system whereas the position of the body does not influence the ECG (15). The triangular lead system is preferred to the standard lead system since there is no dependency on position of the limbs. In addition, the triangular lead system takes into consideration anatomic and topographic particularities of the minipig, relative to other species, such as the dog. Furthermore, the amplitude of waves is greater in triangular leads than in limb leads. Kinter and co-workers (7) reported that, in minipigs, traditional limb electrocardiography may be sub-optimal for evaluation of the QT-interval and that the axial lead is preferred.

For limb leads, the position of the electrode affects the ECG. Position-1 electrodes on the cubital and stifle joints are preferred since the P- and R-waves were clearly identifiable with amplitude > 0.2 mV. This is particularly important when manual reading of ECGs is performed. Also, the T-wave amplitude is (positive or negative) > 0.2 mV in at least two leads, making the determi-

Table 7. The T-wave amplitude (mV) and T-wave area recorded from male and female minipigs (n = 12). Electrodes were placed on the cubital and stifle joints for standard limb leads and on the neck, sacrum and xyphoid process for triangular leads

	Lead											
Variable	I	II	III	aV_R	aV_L	aV_F	Dorsal	Axial	Ventral	aV_R-dorsal	aV_L-axial	aV_F-ventral
Positive T-wave												
Mean	0.15	0.32	0.26	0.13	0.20	0.20	0.29	0.51	0.24	0.36	0.07	0.28
SD	0.04	0.14	0.15	0.12	0.12	0.11	0.21	0.48	0.26	0.15	0.02	0.21
Min	0.11	0.15	0.07	0	0.09	0.09	0.03	0.08	0.04	0.18	0.05	0.15
Max	0.19	0.62	0.6	0.29	0.4	0.38	0.68	1.38	0.8	0.66	0.1	0.59
Negative T-wave												
Mean	-0.14	-0.29	-0.36	-0.10	-0.39	-0.22	-0.16	-0.24	-0.13	-0.34	-0.11	-0.35
SD	0.09	0.29	0.44	0.09	0.31	0.24	0.06	0.11	0.04	0.21	0.10	0.13
Min	-0.32	-0.86	-0.86	-0.24	-0.75	-0.69	-0.23	-0.36	-0.19	-0.62	-0.31	-0.55
Max	-0.02	-0.08	-0.06	0	-0.2	-0.01	-0.07	-0.05	-0.09	-0.14	-0.01	-0.13
T-area												
Mean	-2.14	2.21	3.49	2.10	-0.31	-0.97	2.15	4.72	5.83	1.92	-1.82	-3.64
SD	4.99	12.40	11.95	6.56	11.70	9.67	10.10	20.62	12.16	15.73	3.86	12.97
Min	-9.25	- 28.14	-28.7	-7.83	-28.2	- 22.12	-10.31	- 14.62	-5.24	-24.45	-9.62	-17.05
Max	5.86	16.06	19.75	11.39	11.58	10.05	19.97	50.01	29.2	22.79	2.71	24.6

Table 8. QT and ST intervals recorded in position 1 from male and female minipigs (n = 12). Electrodes were placed on the cubital and stifle joints for standard limb leads and on the neck, sacrum and xyphoid process for triangular leads

	Lead											
Variable	I	II	III	aV_R	aV_L	aV_F	Dorsal	Axial	Ventral	aV_R-dorsal	aV_L-axial	aV_F-ventral
QT-interval (msec)												
Mean	283.6	289.7	291.5	306.2	298.4	299.4	290.8	296.2	293.8	298.9	291.5	296.2
SD	26.7	21.8	18.7	25.2	23.3	19.7	22.0	26.9	20.3	15.2	15.1	26.5
Min	255.7	255.7	264.9	273.7	253.2	263.4	266.6	260.2	262.8	273.7	260.7	255.1
Max	332.1	319.7	322.9	345.3	339.0	327.0	331.8	337.9	329.5	320.1	312.1	332.9
ST-interval (msec)												
Mean	158.5	168.4	166.0	169.0	176.1	170.4	169.0	174.0	165.5	166.0	162.2	169.9
SD	18.8	18.4	21.0	23.3	18.4	15.5	15.1	18.5	24.4	18.2	20.9	28.9
Min	130.2	134.5	136.9	130.6	145.9	135.2	146.6	134.3	138.7	131.1	120.8	103.1
Max	191.5	199.9	208.3	212.1	208.0	190.3	192.5	199.3	209.0	190.5	191.0	206.2

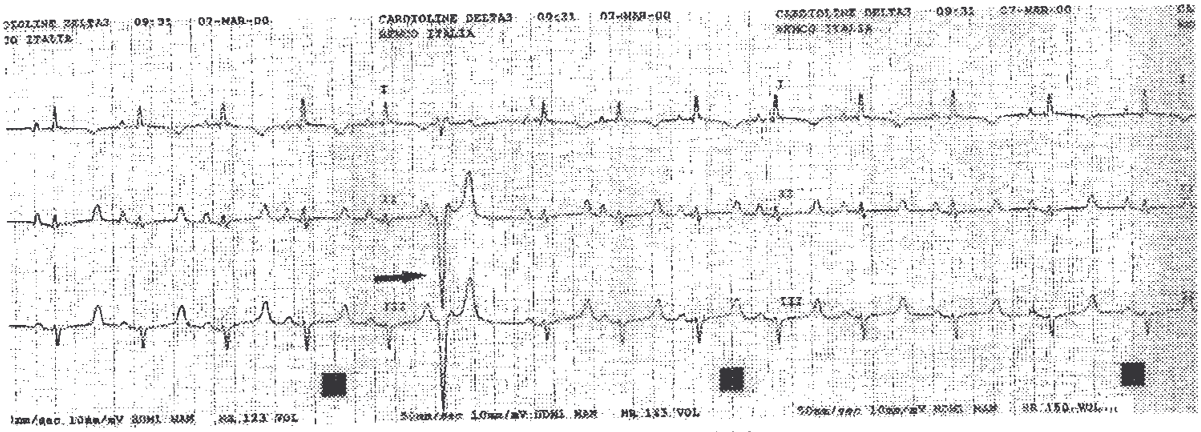

Figure 4. Ventricular premature beat (arrow) in a limb lead ECG recorded from a minipig.

nation of the QT-interval accurate.

For the triangular leads, the position of the electrode has less influence on the amplitude of deflections. However, if the axial lead is to be used for calculation of intervals and amplitudes, the xyphoid process (position 1) is the preferred position. For this lead, all amplitudes are > 0.2 mV.

The QRS patterns were determined from paper-recorded ECGs at the chart speed of 50 mm/sec and sensitivity of 10 mm/1mV. Therefore, the Q- and S-waves were of small amplitude (< 0.5, boxes = mm) and not easily distinguished from the base line. Using automated analysis with amplification of the signals allowed more accurate determination of patterns. This explains the slight discrepancy between the patterns reported in Table 3 and what can be concluded from the Q and S amplitudes reported in Table 4. However, this discrepancy has no impact when comparing limb leads with triangular leads. Concerning QRS patterns in limb leads, our results are in complete disagreement with those of Dukes and Szabuniewicz (4). This could be attributed in part to the position of the electrodes. However, the position used by those authors was similar to our position 2. If the position of the

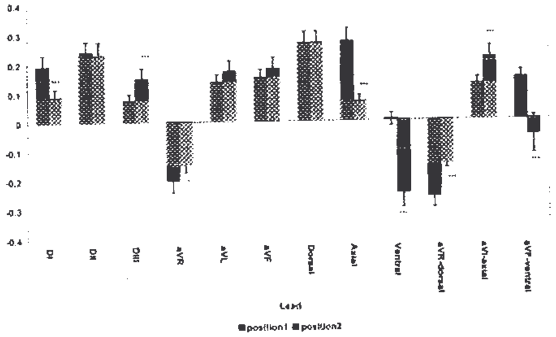

Figure 5. Effects of the position of the electrodes on P-wave amplitude. In position 1, electrodes were placed on the cubital and stifle joints for standard limb leads and on the neck, sacrum, and xyphoid process for triangular leads. In position 2, electrodes were placed on the cranial edge of the scapula and thigh for standard limb leads, and on the neck, sacrum, and sternal manubrial process for triangular leads. Values are mean confidence interval, and are statistically significant from position 1 at $P <$ *0.05, **0.01, and ***0.001, respectively.

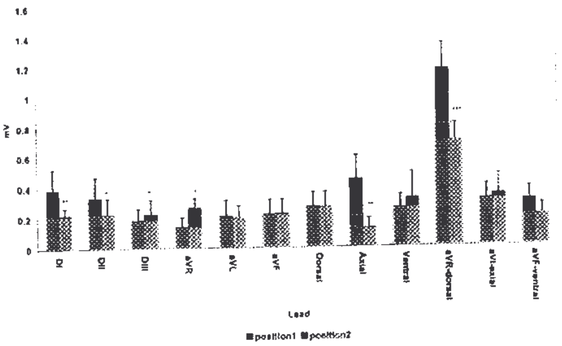

Figure 6. Effects of the position of the electrodes on R-wave amplitude. In position 1, electrodes were placed on the cubital and stifle joints for standard limb leads and on the neck, sacrum, and xyphoid process for triangular leads. In position 2, electrodes were placed on the cranial edge of the scapula and the thigh for standard limb leads and on the neck, sacrum and sternal manubrial process for triangular leads. *See* Fig. 5 for key.

electrode has no influence on the QRS patterns, the strain and age of pigs used may have contributed to this variability.

Our results, either for limb leads or triangular leads, are comparable to those reported for Göttingen minipigs (7), confirming the validity of the IOX software we used for automated ECG analysis. Spontaneous ventricular premature beats in minipigs also have been reported (16).

In conclusion, the triangular lead system is recommended for recording ECGs in minipigs. Limb leads could be used in addition. The cubital and stifle joints for standard limb leads and the neck, sacrum, and xyphoid process for triangular leads are the preferred positions for the electrodes.

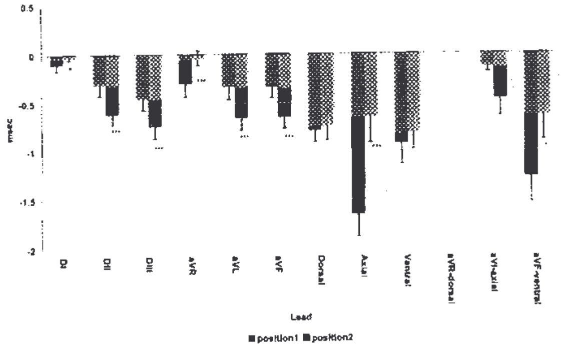

Figure 7. Effects of the position of the electrodes on S-wave amplitude. In position 1, electrodes were placed on the cubital and stifle joints for standard limb leads and on the neck, sacrum, and xyphoid process for triangular leads. In position 2, electrodes were placed on the cranial edge of the scapula and the thigh for standard limb leads and on the neck, sacrum, and sternal manubrial process for triangular leads. *See* Fig. 5 for key.

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