FUNDAMENTAL STUDIES ON ELECTROCARDIOGRAMS OF THE HORSE

I. UNIPOLAR SEMIDIRECT LEAD

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INTRODUCTION

Since TSCHERMAKIM's report, investigations of the electrocardiogram in the horse have been carried out, but several problems for solution, as pointed out by KUSACHI and NISHIDA, remain untouched.

Concerning the method of lead, TSCHERMAKIM's report contributed no data. KAHN adopted the lead from the right side of the neck to the left under chest. NÖRR applied 3 kinds of bipolar leads to horse together with other domestic animals; the first limb lead as used in man, the second lead connected from the front chest to the left under chest and the third lead connected from oesophagus to rectum. He recommended the second lead because he was able to obtain tracing which was free from artifacts and of practical convenience. LAUTENSCHLAGER proposed that the electrodes should be connected to those regions where the electrical axis of the heart terminated. STEFFAN[22,23] tried the lead from the left under thoracic wall to *regio praescapularis*, in accordance with LAUTENSCHLAGER's proposition and applied this lead clinically. Recently KUSACHI and NISHIDA examined heart function during free bleeding by the same lead. In order to establish the lead from which electrocardiograms similar to those in man could be obtained, NEUMANN-KLEINPAUL and STEFFAN tried to lead from combinations of 19 points on the body surface of the horse and proposed the use of 3 leads; the first lead from the left under chest to *regio praescapularis*, the second from the left under chest to rectum and the third from *regio praescapularis* to rectum. YASUDA and associates applied NEUMANN-KLEINPAUL's 3 leads to military horses. Since LILLEENGEN and OTTOSSON employed the limb lead as in man in the horse of ROKITANSKY's defect, this lead has been usually employed clinically. Criticizing the limb lead and the 3 leads proposed by NEUMANN-KLEINPAUL, UEDA and associates pointed out that the EINTHOVEN triangle theory was not taken into account in planning these leads, because of the eccentric position of the heart in the horse and tried unipolar lead, placing the indifferent electrode in rectum. Recently LANNEK and RUTQVIST presented normal area of variation of electrocardiograms obtained both by limb lead and by chest lead when the indifferent electrode was WILSON's terminal electrode. However, as UEDA and associates and KASHIDA and KIMURA pointed out, the limb lead used in the horse as in man is not equivalent to that in man, because of the

different position of the heart anatomically speaking. The heart of the horse is eccentric in the body, near the forelegs, especially the left foreleg. So the EINTHOVEN triangle theory is not valid in the horse when the limb lead is used. It is moreover evident that so-called WILSON's terminal electrode cannot be employed, using unipolar lead. Generally speaking, this fact holds true for four-footed animals. Therefore, the method of lead in the horse should be examined not only from a veterinary clinical point of view, but also as connected with the field of human medicine. In addition to the above mentioned references, a study on electrocardiogram of the horse by DUKE and BATT has been noted, but as the original was not obtainable, no reference is made to it.

When unipolar leads are used, it is problematical how to put the indifferent electrode on a point which will maintain as nearly as possible a constant potential. As the writer considered that WILSON's electrode is of no use in the horse, in the present paper indifferent electrode was placed on the under side of root of the tail, which is a suitable spot to put the electrode because of its being a hairless position. The purpose of the present paper is to describe the subject of how depolarization travels in the equine heart, from the results obtained by the above mentioned unipolar semidirect lead.

MATERIAL AND METHOD

Four normal healthy horses from 6 to 8 years old, were examined. They were mongrel Percheron including 2 females and 2 geldings. For recording the electrocardiograms, a battery-driven electrocardiograph, differential ampliphier whose time constant was 1.5 second, Type UD-4, manufactured by Fukuda Co. Ltd. Tokyo, was used. This apparatus registers 3 leads synchronously and makes vertical marks every 20th second, regardless of the rate of the paper. The sensibility was so corrected as to make 1 millivolt correspond to an amplitude of 20 millimeters in order to observe the P wave in detail. The indifferent electrode consisted of a quadrangular metal plate (size 2×4 cm) which was fastened with bandage on the under side of root of the tail. A gauze soaked with saturated natrium chloride solution was applied between the surface of skin and the electrode. A clip (size 0.5×5.0 cm) was used conveniently for the different electrode. For good conduction through the isolating coat of hair, a gauze soaked with saline solution was also put between the clip and the region sufficiently moistened with the solution, from which electrical changes were lead. Of course, the electrodes were, in accordance with electrographic convention, arranged so that the registration showed upward deflection when the different electrode faced the relative positive potential against the indifferent electrode and downward deflection when the different electrode faced the relative negative potential against the indifferent electrode.

The registration was carried out with the horse in a standing position with the front extremities, if possible equally loaded. The horse had been rested before the examination.

The electrocardiograms thus obtained when the exploring electrode was transferred from one point to the other in succession, relatively near the heart were observed.

EXPERIMENTAL RESULTS

Experiment 1

Three out of the 4 horses were examined. The unipolar leads were taken from 18 points, as showed in fig. 1, on a circular line running vertically behind the back edge of the olecranon and through the withers, which were equidistant from each other. Each distance was from 11 to 12 cm. In fig. 1, point 0 is on the withers and point 5 is at the same horizontal level as the shoulder joint. Point 6 is at the same height as a horizontal line through the highest point of the olecranon.

Hereafter position 5 on the left side or on the right side will be denoted respectively by L_5 or by R_5. The other points can be denoted similarly. Then, the points between L_5 and L_8 face over the left ventricle, while L_8 is nearly over the greater part of the right ventricle. The points between R_5 and L_5 face over the posterior portion of the base of the heart.

1) The P wave (Figs. 2 and 3): As reported in the previous paper[12], the P wave was generally complicated, but the type which had 3 extremes was usually observed. The configuration of the P wave could be also expressed either by W-form or by inverted W-form (Fig. 2). Therefore, when the amplitudes of the extremes were measured, 3 values which were expressed respectively as the amplitude of P_1, as the amplitude of P_2 or as the amplitude of P_3 were generally obtained. The changes of the minimum or of maximum amplitudes of extremes in the P wave are shown graphically in fig. 3. On the withers, maximum of negative value was obtained. The positive amplitudes of the wave were observed under L_3 or under R_7 and the positive maximum existed on L_6. These facts were observed in the 3 examined horses. Therefore, it is concluded that the directions in which the depolarization spreads in the auricles have great component that repairs immediately behind the back edge of the olecranon.

2) The Q wave (Figs. 2 and 4): The Q waves were observed only between position 0 and L_4, but did not come out in one case.

3) The R wave (Figs. 2 and 4): The amplitude of R wave attained maximum on L_1-L_2 and its changes were large both between R_1 and R_3 and between L_4 and L_6. Between R_3 and R_5, the second maximum existed. It attracts attention that notching upon down-stroke was observed on L_5 or on R_5. The intrinsicoid deflections came from 0.009 to 0.011 sec. after the beginning of QRS complex both between L_5 and position 9 and between R_6 and position 9; from 0.017 to 0.021 sec. such deflection occurred between L_5 and R_5.

4) The S wave (Figs. 2 and 4): The waves were represented both under R_6 and under L_5. Maximum of the amplitude was about on L_7. Transitional zone existed both between R_6 and R_7 and between L_5 and L_6.

5) The T wave (Figs. 2 and 4): The feature was diphasic in all 3 cases. Between R_5 and L_4, it was plus minus type; between L_5 and position 9 or between R_6 and position 9, minus plus type; frequently it was monophasic negative on L_6. The positive (upward) amplitude showed maximum about on L_3 or on R_7 and the negative (downward) amplitude showed maximum about on L_1 or on L_7.

FIG. 1. *Positions on which the Different Electrodes were Placed in Experiment 1*

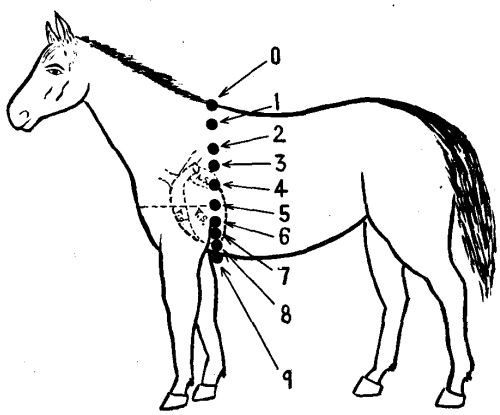


FIG. 2. *Electrocardiograms Obtained with Unipoloar Lead in Experiment 1* (No. 1)

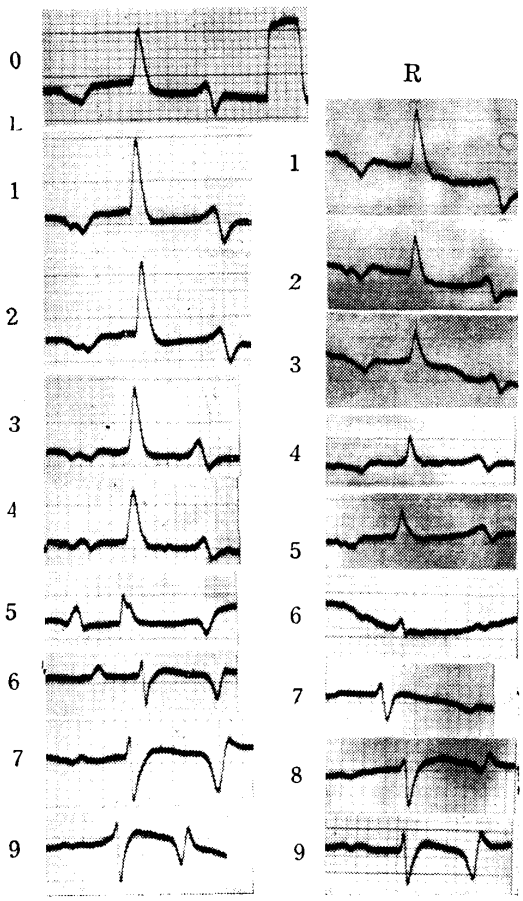


FIG. 3. *Amplitudes of P Wave in Experiment 1* (No. 1)

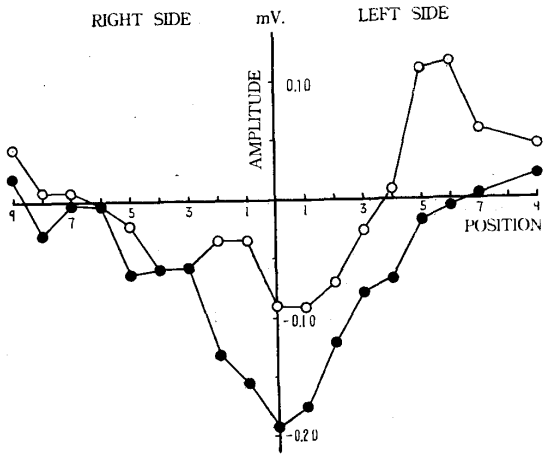
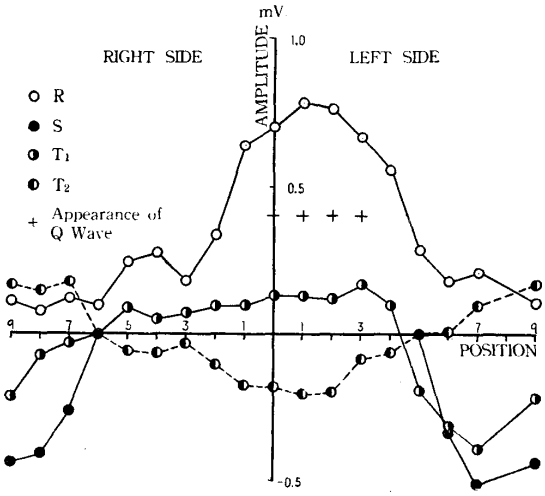


FIG. 4. *Amplitudes of QRS Complex and T Wave in Experiment 1* (No. 1)



Experiment 2

Two out of the 4 horses previously mentioned were examined. Unipolar leads were taken from 13 points, as shown in fig. 5, at the same horizontal level as the shoulder joint; all points were equidistant from each other. Each distance was from 13 to 14 cm.

Point 0 is then on the under midline and point 2 corresponds to the shoulder joint. It is anatomically estimated that R_5-L_2 face both over the right auricle and over the upper portion of the right ventricle and that L_3-L_5 face both over the left auricle and over the left ventricle.

1) The P wave (Figs. 6 and 7): Three extremes of the wave were measured and showed in fig. 7. It was found that the negative maximum existed on R_2 and the positive maximum was represented on L_6. These results show the fact that depolarization spreads in the direction from R_2 to L_6 in the auricles.

2) The Q wave (fig. 6): Between L_6 and R_4, the waves were noticed slightly.

3) The R wave (Figs. 6 and 8): The amplitude reached its maximum on L_1. Between L_1 and L_4, changes of the amplitude were small, but they were large both between R_3 and L_1 and between L_4 and L_6. It was also noticed that the second maximum existed in the neighbourhood of R_4. It should be also noticed that notchings were observed between R_4 and L_4 and frequently on L_6. Between R_4 and L_4, notchings on upstroke were recorded and on L_6, notching on downstroke was frequently observed. The height of notching (R prime) indicated maximum of point 0 and gradually decreased, as the electrode was moved from point 0 to R_6.

4) The S wave (Fig. 6): In this region, the wave was not observed.

5) The T wave (Figs. 6 and 8):

FIG. 5. *Positions on which the Different Electrodes were Placed in Experiment 2*

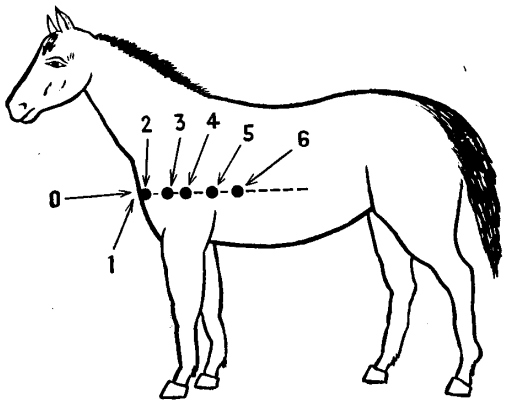


FIG. 6. *Electrocardiograms Obtained with Unipolar Lead in Experiment 2* (No. 1)

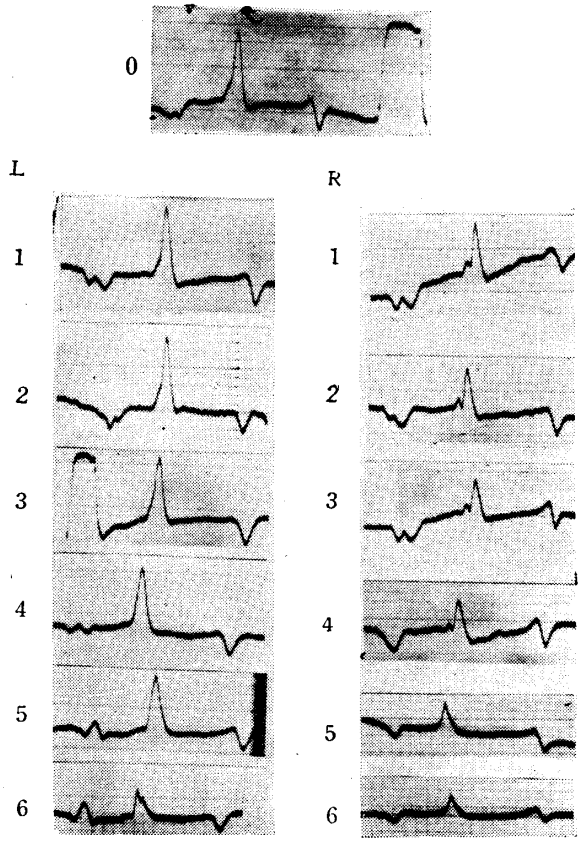


FIG. 7. *Amplitudes of P Wave in Experiment 2* (No. 1)

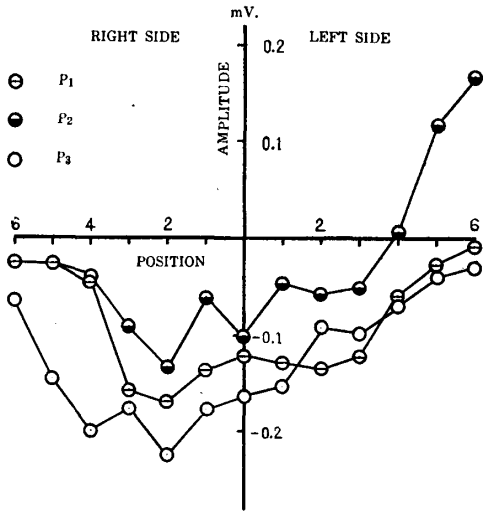
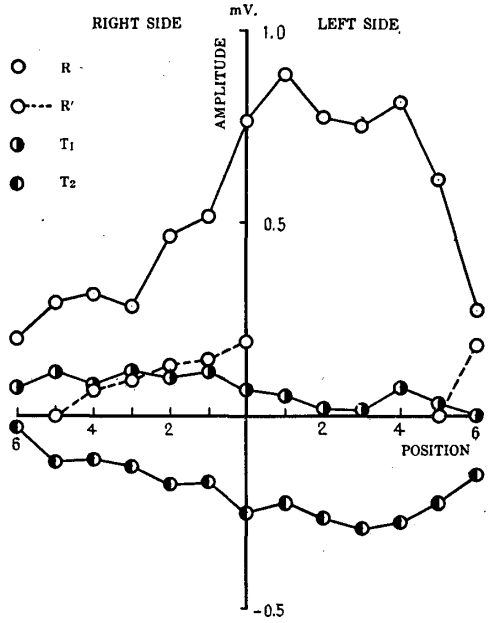


FIG. 8. *Amplitudes of QRS Complex and T Wave in Experiment 2* (No. 1)

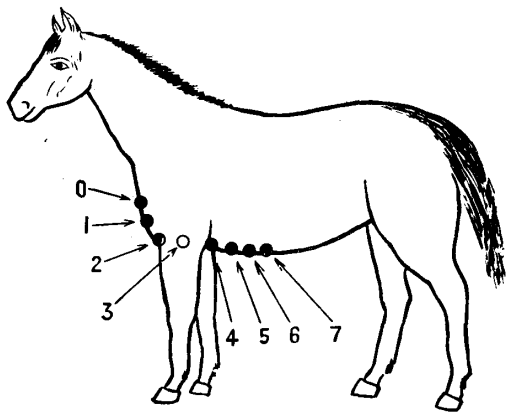


The diphasic T waves were plus minus type on these positions. But it was almost a monophasic wave, as the positive part became very small between L_2 and L_6. The positive amplitude of the wave was greatest between R_1 and R_5, and decreased gradually as the electrode was moved to L_6 on the left side. The negative amplitude showed maximum on L_3 and decreased gradually on both sides of L_3.

Experiment 3

Two out of the 4 horses were examined. Unipolar leads were taken from 8 equidistant points, as shown in fig. 9, on the under midline. Each distance was about 10 cm. Point 0 is at the same height as the shoulder joint. Position 4 is on the line connecting the both olecranons. It is estimated that positions 0, 1, 2 and 3 face over the right ventricle, that positions 4 and 6 face over the left ventricle and that position 4 or 5 faces about over the apex of the heart.

FIG. 9. *Positions on which the Different Electrodes were Placed in Experiment 3*



1) The P wave (Figs. 10 and 11): The negative amplitude, especially P_3, was maximum on position 5.

2) The Q wave (Fig. 10): Between positions 0 and 2 the waves were slightly observed and markedly represented on

FIG. 10. *Electrocardiograms Obtained with Unipolar Lead in Experiment 3* (No. 2)

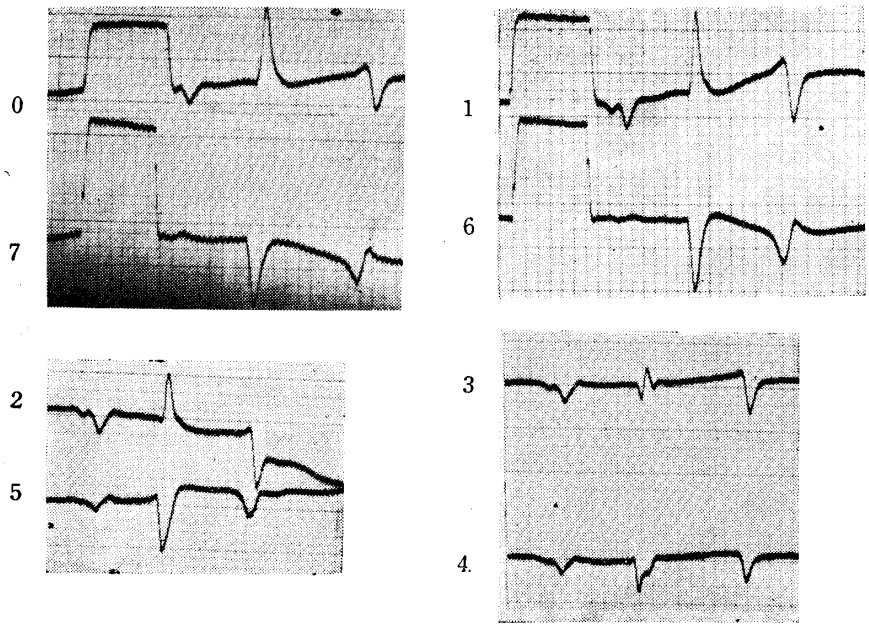


FIG. 11. *Amplitudes of P Wave in Experiment 3* (No. 2)

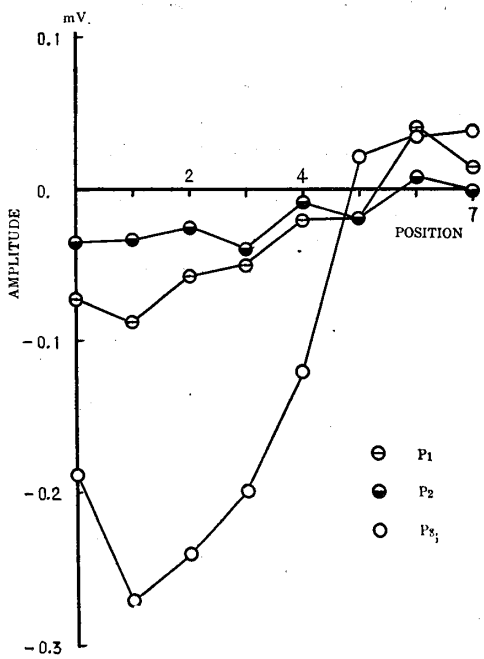
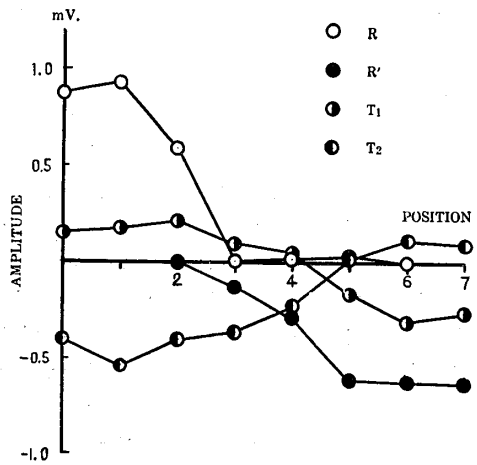


FIG. 12. *Amplitudes of QRS Complex and T Wave in Experiment 3* (No. 2)



position 3.

3) The R wave (Figs. 10 and 12): The maximum amplitude was found on position 1. Between position 1 and 3 the amplitude decreased notably and disappeared about on position 6.

4) The S wave (Figs. 10 and 12): The waves came out on point 2 and increased conspicuously, as the electrode was moved toward position 5. In the rear of position 5, no changes were observed. It was noticed that notching on upstroke appeared on position 4.

5) The T wave (Fgis. 10 and 12): In front of position 4, this wave showed plus minus type and minus plus type in the other positions. On position 5 faced over the apical region of the heart, it was almost monophasic negative wave.

Experiment 4

Two out of the 4 horses were examined. Unipolar leads were taken from the 11 points shown in fig. 13, on the lines connecting the point over the shoulder joint and withers on both sides.

Position 0 is over the shoulder joint and position 2 is the midpoint connecting position 0 and the withers. Position 1 is the midpoint between positions 0 and 2. Position 4 is

FIG. 13. *Positions on which the Different Electrodes were Placed in Experiment 4* (No. 2)

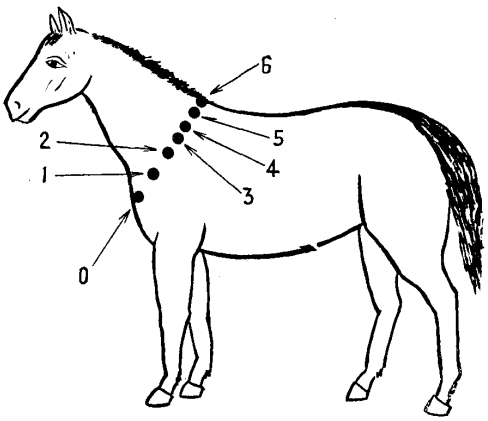
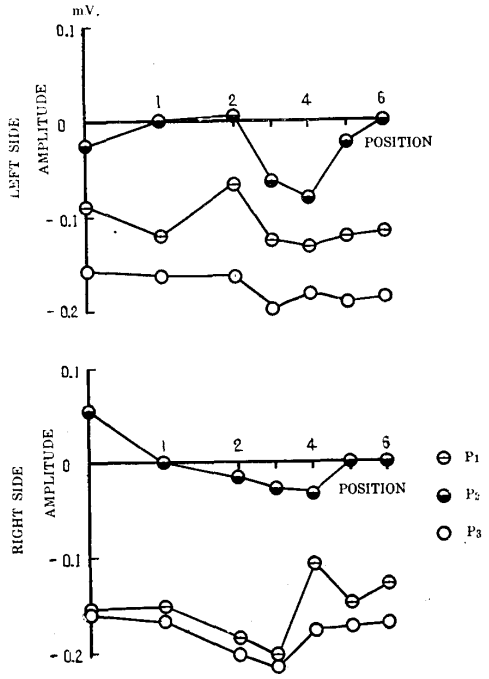


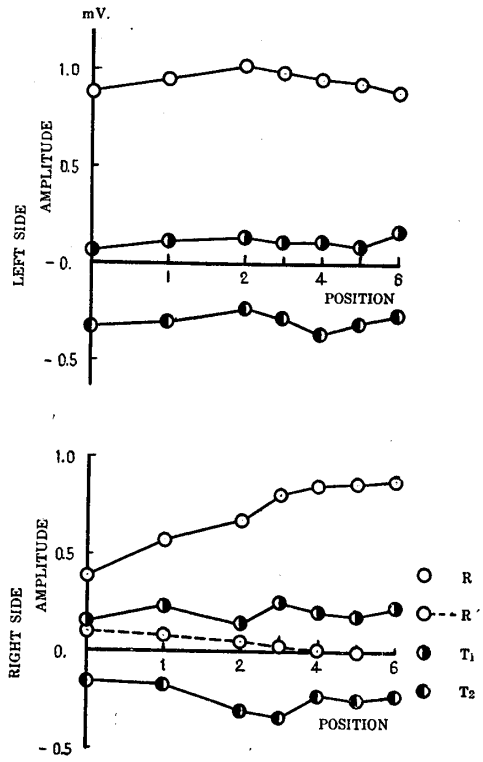
FIG. 14. *Amplitudes of P Wave in Experiment 4* (No. 1)



the midpoint between positions 2 and 6. Then, R_2, R_3 and R_4 face over the base of the heart. R_0 and R_1 face either over the right auricle or over the upper portion of the right ventricle. The points on the left side face either over the left auricle or over the upper portion of the left ventricle.

1) The P wave (Fig. 14): Considerable changes were found both in P_1 and P_2 but not in P_3. On the left side, the positive amplitude came out from position 1 to 2 and the negative maximum was represented on L_4. On the left side, the positive amplitude came out on R_0.

FIG. 15. *Amplitudes of QRS Complex and T Wave in Experiment 4* (No. 1)



2) The Q wave: On these positions, the wave could not be found.

3) The R wave (Fig. 15): On the left side, the maximum of the amplitude was represented between L_2 and L_4. The changes were small on both sides of the maximum. On the right side, the amplitude increased gradually, as the electrode was moved from R_0 to R_6. It was noticeable that notching on upstroke was observed and that the height of notching represented maximum on R_0.

4) The S wave: In this region, the wave could not be observed.

5) The T wave (Fig. 15): The wave was plus minus type and no noticeable changes of the amplitude could be found.

The results of the 4 experiments warrant the following generalizations in respect to QRS complex or T wave.

1) Unipolar leads that face over the epicardial surface of the left ventricle show a qR pattern or an R pattern. T is usually diphasic and minus plus type.

2) Unipolar leads that face over the epicardial surface of the right ventricle show an rS pattern or a QS pattern. T is usually diphasic and plus minus type.

3) Unipolar leads that face over the apical region of the heart show an rs pattern or a qs pattern. T is usually a negative monophasic wave.

4) Unipolar leads that face over the base of the heart show an r pattern. T is usually diphasic and plus minus type.

Experiment 5

One horse was examined only on the left side. Unipolar leads were taken from 21 points distributed on a latticed regular square, as shown in fig. 16. In the figure, line A is at the same height as the midpoint connecting shoulder joint and withers and C is at the same horizontal level as the shoulder joint. Column 3 is on the vertical line through both the withers and olecranon.

1) The P wave (Fig. 17): On column 1, the first positive components were large. The second positive components showed dominancy on column 3.

2) The Q wave (Fig. 17): The wave distributed upwards at a right angle to the long axis of the heart.

3) The R wave (Fig. 17): In the zone connecting E2 and B5, the amplitudes of the

waves were very small or zero. It may be stated in general that the direction of the gradient of the amplitude nearly accorded with the long axis of the heart.

4) The S wave (Fig. 17): Under the zone where the R waves disappeared, the S waves were found. The direction of the gradient accorded with that of the R wave.

5) The T wave (Fig. 17): In this region, the waves were diphasic and plus minus types. The distribution of the first positive amplitudes was similar to that of the amplitudes of the R waves. On the contrary, the second negative amplitudes were distributed diffusely.

FIG. 16. *Positions on which the Different Electrodes were Placed in Experiment 5*

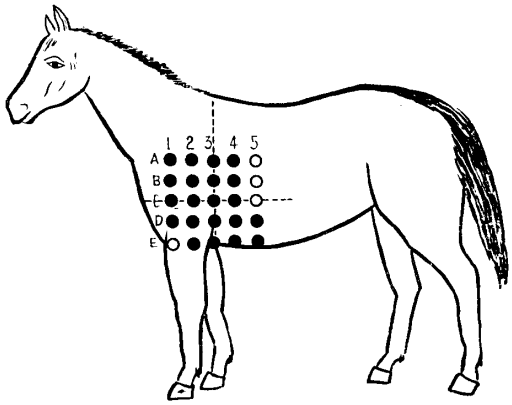
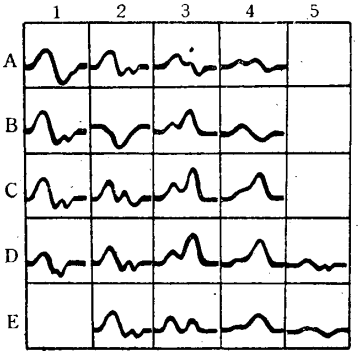


FIG. 17. *Shape of P Wave, Amplitude of QRS Complex and T Wave in Experiment 5* (No. 8)

P



Q (mV.)

		0.024	0.043	
	±	0.056	0.004	
	0.096	0.025		
	±			0 008
				0.026

R (mV.)

1.12	1.01	0.79	0.57	
1.02	0.94	0.56	0.25	
0.86	0.83	0.54	0.01	
1.07	0.55	0.00	0.07	0.04
	0.25	0.07	0.10	0.23

S (mV.)

			0.10	
	0.04	0.15	0.53	
	0.06	0.29	0.73	

T_1 (mV.)

0.10	0.16	0.19	0.10	
0.10	0.07	0.15	0.05	
0.07	0.12	0.12	0.00	
0.06	0.06	0.00	0.00	0.03
	0.00	0.00	0 00	0 06

$-T_2$ (mV.)

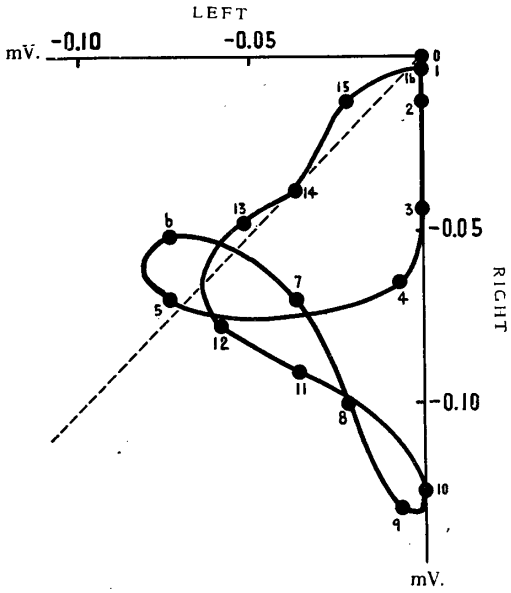
0.32	0.24	0.15	0.10	
0.24	0.27	0.07	0 05	
0.37	0.22	0 11	0.06	
0 24	0.18	0.22	0.34	0.01
	0.35	0.33	0.48	0.05

Experiment 6

In the above described experiments, the relation of the phases in the wave was not examined. So, in this experiment, two unipolar leads from both forelegs were synchro-

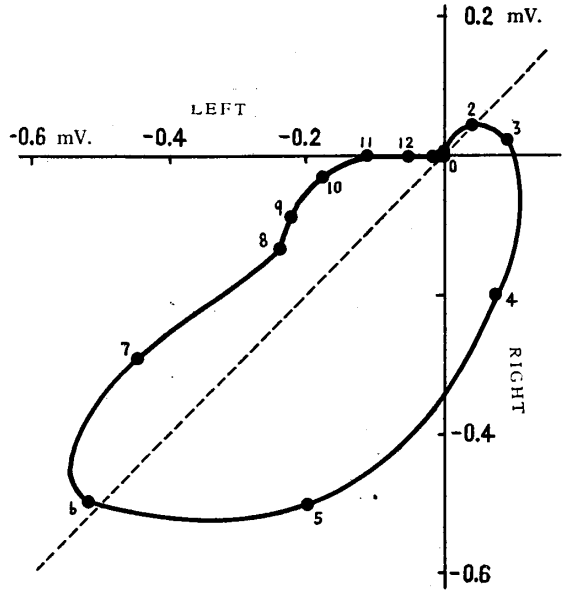
nously registered and the heights of each wave were measured at the same time, every 100th second. When the 2 values measured at the same time were plotted at rectangular coordinate, then patterns as shown in figs. 18, 19 and 20 were obtained. These patterns may be termed a kind of vectorcardiogram.

FIG. 18. *P Pattern*



The numbers attached to the dots show the timecourse in a hundredth second.

FIG. 19. *QRS Pattern*

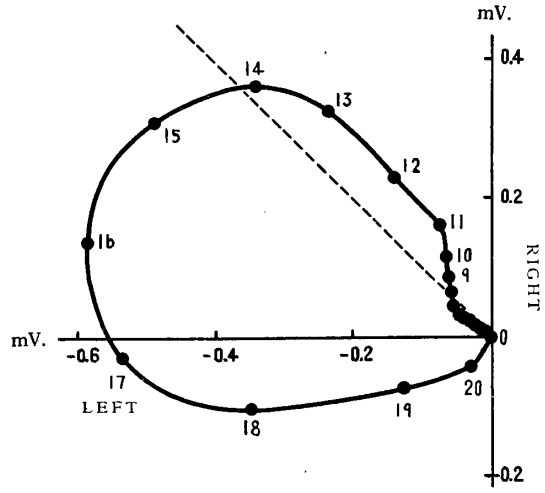


The numbers attached to the dots show the timecourse in a hundredth second.

1) The P pattern (Fig. 18): The pattern is divided into the following 5 phases. a) Only on the right foreleg, the potential change occurs at the first stage. b) The potential change occurs on the left foreleg, but that on the right foreleg is almost constant. c) the potential on the right foreleg increases, but that on the left foreleg decreases at the third stage. d) The relation at the third stage reverses. e) The potentials on both forelegs decrease at the fifth stage. At all stages, the electric changes on the right foreleg show dominancy, in comparison with that on the left foreleg.

2) The QRS pattern (Fig. 19): Roughly speaking, the electrical changes on both forelegs run parallel.

FIG. 20. *T Pattern*



The numbers attached to the dots show the timecourse in a hundredth second.

3) The T pattern (Fig. 20): At first, the electrical change on the left foreleg is inversely proportional to that on the right foreleg.

Discussion

Is it suitable to use Wilson's terminal electrode for the indifferent electrode in horse ? Wilson's electrode bases on the assumption that the sum of 3 potentials on extremities is zero (exactly speaking constant); then the assumption evidently depends on the Einthoven triangle theory. In order that the condition may be met under which the Einthoven triangle theory is accepted, it is theoretically considered that the following 3 conditions should be satisfied, as Kimura pointed out.

1) Electrical source exists in the center of the equitriangle.
2) The conductor has homogeneous conductivity.
3) Extension of the conductor is sufficiently large.

However, as the heart of the horse, and generally speaking, the heart of the quadrupeds is eccentric in the body, that is in the neighbourhood of the forelegs, so the first condition is not satisfied as it is in using limb lead as in man, even if the second and third conditions are satisfied. Therefore, it is not suitable to use Wilson's electrode for the indifferent electrode in the horse nor in other quadrupeds. The fact that Wilson's electrode was unfit to use for the dog was experimentally ascertained by Mauro and his associates, investigating equipotential distribution for the various instants of the cardiac cycle on the body surface of the dog. In writer's experiment, the method of placing the indifferent electrode on the root of the tail was applied to obtain approximate electrocardiograms of unipolar lead, because of no other suitable method. However, it may be considered that this method is passably accurate when the different electrode is applied in the neighbourhood of the heart.

Observing changes of the wave in experiments 1, 2 and 3 it is concluded that the principal direction of excitation traveling in the auricles is from anterior superior right to posterior inferior left, as Ueda and his associates have pointed out.

It may be worthy of note that the P wave has splintering or notching in all horses in writer's experiments. Concerning the notching or splintering of P wave, Hering interpreted that it was caused by the summation of the excitation of sinus node and the contraction of the right auricle or the left and right auricles. Eyster et Meek thought that the negativity of the sinus node came out at first when the stimulus conduction from the sinus node to the auricle was injured, because of the experiment with dogs in which the sinus node became electrically negative from 0.025 to 0.030 second before the right auricle. Groedel explained that it was provoked by the time difference of the contraction of the left and right

auricle. ZÁRDAY indicated that the first and second peak of P wave derived from the right and left auricle respecitively when the wave split.

As for the stimulus conduction in the auricle, it has been accepted that this does not depend on the special heart muscle system as in the ventricle. However, ROTHBERGER et SHERF and CONDRELLI proved 3 conduction bundles anatomically and functionally in dog's heart. TAKAYASU[24~26] observed that the P wave of electrocardiogram recorded by cathod ray oscillograph in man had 3 or 2 waves in almost all cases and considered that the P wave consisted of 3 elemental waves. He considered that the first was caused by the electrical excitation which conducted from the sinus node, to TAWARA's node, the second wave was considered to be obtained when the electrical excitation spread to the right auricle and the third wave was considered to be obtained when the excitation traveled to the left auricle.

From the results of the above experiment 5, it may be authentic that the first peak of P wave is concerned with depolarization of the sinus node or with excitation of the right auricle or with both of the depolarizations, and that the second peak is produced by the left auricle. It is therefore considered that the result of experiment 5 supports the consideration of ZÁRDAY. But the P wave can not be easily divided into the 3 elementary waves which TAKAYASU pointed out. It should be considered that the P wave of semidirect unipolar lead is transformation of P wave of direct lead. Therefore, if the special conduction bundles in the auricles are accepted, it is difficult to conceive that P wave, from the results of the writer's experiments, corresponds to these elementary waves. The time difference of the electrical change of both forelegs from 0.03 to 0.04 second, as the P pattern in fig. 18 shows, is near the value of the time difference of excitation in the auricles obtained by many investigators with direct lead in the dog. So it may be estimated that the time difference of electrical changes of forelegs is due to the time difference of excitation in the auricles. The configuration of P wave in the horse is clearly more complicated than that in man. The reason for this is that the time difference of the auricles is larger than in man because the auricles of horse are larger and more extended,

Unipolar leads that face over the epicardial surface of the left ventricle show a qR pattern or an R pattern. Such a lead also faces the left side of the interventricular septum and the endocardial surface of the right ventricle. As the depolarization spreads through the septum from left to right, it spreads away from this lead. Therefore an initial q is recorded. The result of distribution of Q wave in experiment 6 proves the validity of this explanation. A moment later, the depolarization travels outward through the left ventricle toward the lead and an R wave appears. Depolarization spreads also outward through the right

ventricle, away from the lead. However, it produces less electrical potentials than the left ventricle because the right ventricle is smaller and thinner than the left. Therefore it is not able to counterbalance the electrical potential produced by the left ventricle. These results produce a qR pattern. When the different electrode lies on the same plane as the interventricular septum, unipolar leads show an R pattern because it may not record the depolarization that spreads through the septum.

Unipolar leads that face over the epicardial surface of the right ventricle show an rS pattern. Such a lead also face over the right side of the septum and the endocardial surface of the left ventricle. An initial r wave is due to the spread of the depolarization through the septum toward the different electrode. A moment later, this lead faces strong depolarization spreading way from it, outward through the left ventricle. This counterbalances the weak depolarization which spreads outward through the right ventricle toward the lead and downward deflection appears. The result is an rS pattern.

The above described explanation for a qR pattern or for an rS pattern has been generally accepted in electrocardiography.

Unipolar leads that face over the base of the heart show an r pattern. In accordance with usual knowledge of electrocardiography, these leads should show a QS pattern. PRUITT and associates reported that depolarization traveled upward along the muscle bundle of the left ventricle in the dog. YOSHIMOTO pointed out the same phenomena in man. Therefore the R pattern may indicate that strong depolarization travels upward along the muscle bundle of the left ventricle in the horse. This consideration explains also the reason why unipolar leads that face over the apical region show a qs pattern. Moreover, these results illustrate that the apical area is the site of the fastest depolarization as is already fully accepted in electrocardiography.

T wave of man is usually monophasic in all leads. But T wave of the horse is diphasic plus minus type when the different electrode faces over the epicardial surface of the right ventricle, diphasic minus plus type when the electrode faces over the epicardial surface of the left ventricle and monophasic negative wave when the electrode faces over the left apical region. These results may show that the left apical area is the site of the fastest repolarization that appears earlier in the right ventricle than in the left ventricle and then that the left ventricle is the last region repolarized. However, this explanation for diphasic T wave should be examined further in the future, as diphasic T wave is not only of interest but also important to interpret significance of T wave.

SUMMARY

In this paper, a unipolar and several bipolar leads which have been used for the horse have been criticized, in view of the specific anatomic position of the equine heart in the body. Because of there not being any other suitable lead, by means of the unipolar lead in which an indifferent electrode was put on the root of the tail, a discussion has been presented on the subject of how depolarization traveles in the heart.

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