History of research in Japan on electrocardiography in the racehorse

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Since the first recording of electrocardiograms (ECGs) of a horse in Japan was carried out in 1944, studies on ECGs have been performed intensively. During the early stages of research from the 1950s to 1960s, leads to use for ECG recording were evaluated using several different approaches including unipolar leads, bipolar limb leads, and bipolar chest leads. Based on these studies, the AB lead, which is oriented along the long axis of the heart, became the standard reference method in Japan. Electrodes of the AB lead are placed on the upper 1/4th point along a straight line between the withers and the left shoulder blade (base: B), and 10 cm posterior to the left olecranon (apex: A). The incidence of equine arrhythmias among racehorses has been surveyed, and details of the electrocardiographic characteristics of several arrhythmias have been investigated. In particular, atrial fibrillation (AF) has been extensively studied, and papers have reported findings such as that paroxysmal AF occurs during racing and described electrocardiographic changes that occur at the onset of AF during exercise. Development of a radiotelemetry system for ECG recording enabled the first recording of equine ECGs during galloping in 1964, the detection of arrhythmias, and calculation of heart rate during exercise. Studies on comparative and developmental changes of ECGs have described characteristics of the equine ECGs. Future research on changes in cardiac function, including autonomic function, that occur with aging may lead to new developments in equine electrocardiography and contribute to improving the health and welfare of the horse.

Key words: arrhythmia, electrocardiogram, exercise electrocardiography, horse

In the present day, electrocardiography is a common method of clinically examining racehorses, and it is easy to record clear electrocardiograms (ECGs) from horses by using an electrocardiograph and electrodes that are readily available commercially. However, it was not so easy to obtain clear ECG recordings during the period from the mid-1940s to the beginning of the 1960s, which is when the first attempts at recording equine ECGs were performed during the early stages of ECG research on horses in Japan.

According to a review by Amada [11] on the history of research in Japan on electrocardiography that for domestic animals, the oldest paper on ECGs of cattle was a report by Uesaka in 1943 [83], an ECGs of a horse was reported by Yasuda et al. in 1944 [84], and the number of papers on ECGs of horses increased starting in the mid-1950s.

Sawazaki [64] stated in his review of the history of research in Japan on electrocardiography that for domestic animals, the oldest paper on ECGs of cattle was a report by Uesaka in 1943 [83], an ECGs of a horse was reported by Yasuda et al. in 1944 [84], and the number of papers on ECGs of horses increased starting in the mid-1950s.

Yasuda, who first recorded equine ECGs, recalled in an article in the 10th anniversary issue of Advances in Animal
Electrocardiography [65] that electrocardiography had been introduced to horses in his laboratory in 1939 under the guidance of a human medical researcher, Dr. Okinaka of the University of Tokyo. Thereafter, although studies on ECGs of horses were performed at several veterinary schools and other research facilities, most of them were carried out independently by individual researchers in collaboration with human ECG researchers. Therefore, there was no consensus on electrocardiography standards, electrodes or lead methods for use in horses. In this situation, the Japanese Association of Animal Electrocardiography (the current Japanese Society of Veterinary Cardiology) was established in 1964. This society has since played a major role in advancing equine electrocardiography in Japan.

Studies on Lead Methods for ECG Recording in the Early Stages of Research

In 1944, the first equine ECG in Japan was recorded by Yasuda et al. [84] using a lead method introduced by Neumann-Kleinpaul and Steffan in 1935 [52]. Electrodes were placed on the left chest wall over the region of the heart (LH), the anterior border of the right scapula (RS), and the anus (AN) (Fig. 1), and Lead I was referred to as the voltage between LH and RS, Lead II was the voltage between LH and AN, and Lead III was the voltage between RS and AN. They recorded ECGs from 10 warhorses and reported that the PQ intervals were 0.225–0.30 sec and QT intervals were 0.40–0.47 sec. Wenckebach-type atrioventricular block (AV block) was observed in a horse. In addition to these findings, Yasuda provided detailed explanations of electrocardiography that were cutting edge techniques at the time.

In 1955, Kusachi [29] recorded ECG by using five different unipolar lead methods and placing many electrodes on the right and left chest wall; for example, 18 electrodes were placed at equal intervals on a circular line running vertically behind the back edge of the olecranon and through the withers (Fig. 2), or 13 electrodes were placed at a level horizontal to the shoulder joint. An indifferent (grounding) electrode was placed on the underside of the base of the tail in all leads. ECG waveforms obtained from each lead were analyzed with respect to the specific position of the equine heart in order to describe how the depolarization wave travels through the equine heart.

In addition to unipolar leads, Kusachi and Sato [30] reported four different methods of using bipolar leads (Lead A, B, C, and D) in 1955 as follows:

A) Lead A was obtained from the left foreleg (LF), the right foreleg (RF), and the left hind leg (H): Lead I was the voltage between LF and RF ($I=LF-\text{RF}$), Lead II was the voltage between LH and RF ($II=\text{LH}-\text{RF}$), and Lead III was the voltage between LH and LF ($III=\text{LH}-\text{LF}$) (Fig. 3). He defined this lead as the standard limb lead.

B) Lead B was obtained from the left foreleg (LF), the right foreleg (RF), and the withers (W): $I=\text{LF}-\text{RF}$, $II=\text{W}-\text{RF}$, and $III=\text{W}-\text{LF}$ (Fig. 4).

C) Lead C was obtained from midway on the straight line connecting the right shoulder joint and the withers (RM), the left foreleg (LF), and midway on the straight...
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D) Lead D was obtained from the 10th left intercostal space at the same horizontal level as the shoulder joint (IC), the left foreleg (LF), and the LM: I=IC–LF, II=LM–LF, and III=LM–RM.

They analyzed ECGs obtained from these four bipolar leads and stated that although Lead A was commonly employed in horses, only electrical changes occurring on the horizontal plane were measured by this method and that it was not equivalent to the limb leads used in humans. Therefore, they suggested it might be necessary to observe changes in electrical activity that occur on a vertical plane that reflects the long axis of the heart. Considering this issue and from the viewpoint of practical convenience, they concluded that Lead B should be the recommended lead for use in the horse. Kusachi wrote interpretive articles in a journal for veterinarians on equine electrocardiography, which, at that time, was a new diagnostic technique [31, 32].

Nakamura et al. [47] recorded ECGs using bipolar limb leads in 1955. While Kusachi [29] placed electrodes on the inner side of the right and left forelimbs at a point about 2 cm above the chestnut and the anterior surface of the left hock, Nakamura et al. placed electrodes on the posterior surface of the right and left olecranons and the anterior surface of the point of the left patella.

Two types of bipolar chest leads were also investigated by Nakamura et al. in the same year [48]. For one type, electrodes were placed on the left olecranon (LO), the right olecranon (RO), and the withers (W), and they defined Lead I as the voltage between LO and RO, Lead II as the voltage between W and RO, and Lead III as the voltage between W and LO, respectively (Fig. 5). In an alternative bipolar chest lead, the left shoulder blade (LS), the region of the apex of the heart on the left side (AHL), and the withers (W) were used as electrode locations, and Lead I was defined as the voltage between LS and AHL, Lead II was defined as the voltage between W and AHL, and Lead III was defined as the voltage between W and LS, respectively (Fig. 6). The main deflections of the QRS complex obtained by Lead II were positive, and the T wave showed a biphasic waveform from positive to negative. This may have been due to setting W to be plus (+) and AHL to be minus (−).

Nakamura et al. [49] also reported using a semi-unipolar chest lead to elucidate heart function. They did this by placing 9 electrodes in the region of the heart on both sides of the chest walls (Fig. 7), with an indifferent (grounding) electrode placed on the anus.

They concluded through these series of experiments that the limb lead might not be suitable for clinical use in horse because the full range of the electrical changes occurring in the heart were not completely traced. On the other hand, they considered that both of the bipolar chest leads used in the study might be applicable for daily clinical diagnosis and that the semi-unipolar chest lead might be useful for...
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At the same time as the studies of Kusachi and Nakamura, Too et al. [78] recorded ECGs of a Percheron using bipolar chest leads by placing electrodes on the left shoulder blade, the region of the apex of the heart on the left side, and the withers. ECGs obtained with Lead II from the region of the apex of the heart on the left side and the withers were analyzed. The P waves were negative, and the QRS complexes and T waves were positive on these ECGs. They analyzed 25 consecutive beats and reported that the P wave duration was 0.085–0.135 sec, the PQ interval was 0.354 sec on average, the QRS duration was 0.075–0.125 sec, and the QT interval was 0.475–0.575 sec. Second-degree AV block was observed in this horse. Furthermore, Too et al. [79] recorded the ECG of a Percheron using a bipolar chest lead by placing electrodes on the right and left olecranons and the withers. Fifteen consecutive beats obtained with Lead II from the right olecranon and the withers were analyzed. Triphasic flat P waves, positive QRS complexes, and positive T waves were observed. Premature ventricular contractions were detected in this horse.

**Fig. 5.** Bipolar chest lead used by Nakamura et al. (1955b). Electrodes were placed on the left olecranon (LO), the right olecranon (RO), and on the withers (W). Lead I was defined as the voltage between LO and RO, Lead II was defined as the voltage between W and RO, and Lead III was defined as the voltage between W and LO.

**Fig. 6.** Bipolar chest lead used by Nakamura et al. (1955b). Electrodes were placed on the left shoulder blade (LS), over the region of the apex of the heart on the left side (LHA), and on the withers (W). Lead I was defined as the voltage between LS and LHA, Lead II was defined as the voltage between W and LHA, and Lead III was defined as the voltage between W and LS.

**Fig. 7.** Semi-unipolar chest lead used by Nakamura et al. (1956). The nine electrodes were placed over the heart region on the left sides of the chest wall. Position 1 is at the median portion of the 6th left intercostal space; position 2 is at the lower part of the 6th left intercostal space; position 3 is at the back of the xiphoid; position 4 is at the upper part of the left olecranon; position 5 is at the median portion of the 2nd left intercostal space; position 6 is 20 cm above position 5; position 7 is located on the right chest wall at the median portion of the 6th right intercostal space; position 8 is at the lower part of the 4th intercostal space; and position 9 is at the median portion of the 2nd intercostal space.

**Investigations of Lead Methods for ECG Recording Performed by the Japan Racing Association**

In order to demonstrate maximum performance at a race, a racehorse must have a sound and fit cardiopulmonary system, especially the heart. The Japan Racing Association’s Equine Health Laboratory (the current Equine Research Institute) was established in 1959 and has been performing research on cardiac function, including ECGs, during exercise in studies conducted by the Exercise Physiology
Section since then.

In 1960, Senta and Nomura [66] recorded ECGs using a chest lead by placing electrodes on the withers and at the intersection of the center axis of the sternum and a line drawn perpendicular from the withers. Action potentials measured by this lead method were sent by a transmitter located near the horse to a receiver located in a laboratory in a different building using a 20 MHz carrier wave. After the high-frequency component and noise were filtered, the ECG was recorded by a two-element electromagnetic oscillograph. Although the ECGs obtained were not as clear as expected, they stated that the reason they used this lead was to investigate sequential changes of R waves, and that detecting R waves was regarded as important. They also stated that a standard lead method for recording equine ECGs had not yet been established at that time. This lead method was used in another study that examined diurnal variations in heart rate [67].

In 1964, Amada and Senta [1] employed a bipolar chest lead method that was oriented along the long axis of the heart. They reported that this was done so that it could obtain stable waveforms and large amplitudes of ECGs in order to detect and analyze equine arrhythmias. Electrodes were placed on the right shoulder (shoulder: S) and the over the region of the left side above the heart apex (apex: A). The exact position of the right shoulder (S) was defined as the upper 1/4th point along a straight line drawn between the withers and the right shoulder blade, and the region of the apex (A) was defined as 15 cm posterior to the left olecranon (Fig. 8). This lead method was referred to as the apex-shoulder lead (AS lead).

ECGs were recorded from 154 horses consisting of 95 young racehorses (2-year-old: not yet having raced) and 59 adult racehorses (3- to 7-year-old: having already raced) by using a direct heat stylus cardiograph set with a time constant of 2 sec. Sensitivities were set at 1 mV=1 cm for a young racehorse and 1 mV=0.5 cm for an adult racehorse. A silver plate (1.5 × 1.5 cm) was used as an electrode material, and a modified charging clip was used as an electrode. When the electrode was attached to a horse’s body, gauze filled with saturated saline was used between the electrode and the skin to improve electrical conductivity. They performed detailed analyses of waveforms, durations, and amplitudes of each wave of the ECGs (Fig. 9) and reported the following major findings: 1) The P wave was observed to be bimodally positive in most cases. Its average amplitude was 0.3 mV in a young racehorse and 0.34 mV in an adult racehorse. The average duration was 0.13 sec in a young racehorse and 0.15 sec in an adult racehorse. 2) In most cases, the PQ segment was slightly displaced in the negative direction. 3) The waveform of the QRS complex was observed as an rS or QS type. The average amplitude of the S wave was larger in an adult racehorse (3.24 mV on average) than in a young racehorse (2.40 mV on average). The average duration was 0.11 sec in a young racehorse and 0.12 sec in an adult racehorse. 4) The T wave showed a biphasic pattern from negative to positive in many young racehorses, whereas, the T wave in the adult racehorse showed a positive monophasic pattern (Amada and Senta 1964a).
on average) in a young racehorse and 0.50–0.23 sec (0.32 sec on average) in an adult racehorse. 6) The QT intervals were 0.54–0.34 sec (0.45 sec on average) in a young racehorse and 0.57–0.34 sec (0.47 sec on average) in an adult racehorse.

According to an article by Nakamura in Advances in Animal Electrocardiography published in 1983 [51], an agreement that the apex-base lead (AB lead) would be used as the standard lead to be applied to animals was adopted at the 6th meeting of the Japanese Association of Animal Electrocardiography held in 1966. The content of this agreement was cited in a review article by Nakamura in 1968 [50] as follows: The position of the electrodes in the AB lead to be used for the horse was determined to be on the upper 1/4th point along a straight line between the withers and the left shoulder blade (base: B), and 10 cm posterior to the left olecranon (apex: A) (Fig. 8). Although the AS lead is thought to be more ideal than the AB lead from the point of view of following the long axis of the heart, the AB lead is easier to use in terms of practicality of setting up.

### Studies on Arrhythmias Observed in Racehorses

From the 1940s to 1960s, although there were a couple of case reports on AV blocks [78, 84] and ventricular premature contractions [79, 80], there was no detailed information published in Japan on arrhythmias, such as the incidence of arrhythmias among racehorses.

Amada and Senta [2] examined the incidence of arrhythmias in 214 horses consisting of 121 young racehorses (2-year-old), 66 adult racehorses (≥3-year-old) and 27 riding horses (≥3-year-old) using the AS lead and identified 48 cases (22.4%) of abnormal ECGs. Arrhythmias observed in this survey were sinus arrhythmia, premature contraction, atrial fibrillation (AF), first-degree AV block, second-degree AV block, sinoatrial block, intra-atrial block, intraventricular block, and WPW syndrome. Details of the arrhythmias observed are in Table 1. Five cases of premature contraction consisted of 3 cases of atrial and 2 cases of ventricular premature contraction. All of these premature contractions were unifocal and had the same coupling intervals. Six cases of Wenckebach-type AV block were observed among 19 cases of second-degree AV block. Ventricular dropped beats in young racehorses occurred sporadically, while ventricular dropped beats in adult racehorses tended to be observed systematically in 4:1 or 5:1 ratios.

When Amada and Senta increased the total number of horses examined from 214 to 250, the number of abnormal findings increased from 48 to 65 cases (26.0%) [4]. Since a total of 19 cases in the original survey were second-degree AV block, the addition of 17 cases of second-degree AV block raised the incidence of AV block among those horses with arrhythmias from 39.6% (19/48) to 55.4% (36/65). Although AV block was one of the most common arrhythmias and usually observed in adult horses as seen in this study, Matsui et al. [41] reported a rare case of second-degree AV block observed in a foal at the age of 2.5 months. They also reported that AV blocks were elicited in both foals and their mares by applying a twitch [44]. Eventually, detailed case reports were published on arrhythmias such as WPW syndrome [68], atrial return echo [69], paroxysmal ventricular tachycardia [70, 72], ventricular parasystole [6], premature atrial contraction [10], and paroxysmal atrial tachycardia with block [14].

The first recordings of AF, which is thought to be one of the most important arrhythmias in the racehorse, were 2 cases reported by Amada and Senta in 1964 [2]. Thereafter, case reports on half-blooded horses [76] and heavy draft horses [81] were published. Several papers on therapy for AF using quinidine sulfate were published as well [3, 5, 8, 12, 24, 38, 81].

Clinical and electrocardiographic observations of 2 cases of AF were published by Amada et al. [8] in 1974. In one horse, physiological parameters including ECG, auriculo-
gram, right atrial pressure, and carotid artery pressure were measured simultaneously in order to clarify the hemodynamics of this condition. According to these measurements, there was a tendency for a ventricular pause to occur when the systolic pressure exceeded 150 mmHg. During the pause, carotid arterial pressure decreased. During several consecutive beats following the pause, both the systolic and diastolic pressures showed stepwise increases. When ECGs during exercise were recorded to examine the response of cardiac function during exercise, a short run of ventricular flutter appeared sporadically during warm-up, and the heart rate (HR) increased abnormally. During a moderate canter, the horse was unable to continue to exercise and showed agonal signs. At that time, the HR increased to 258 beat/min.

Electrocardiographic surveys were conducted following a race on racehorses that finished well behind the winners. In 1975, Amada and Kurita [9] found that 5 horses had developed AF during the race and that all of these had returned to sinus rhythm within less than 23 hr without pharmacological intervention. This paper was the first to report that paroxysmal AF occurred during racing. They also reported that premature atrial contractions were observed in 2 of 5 horses that returned to normal sinus rhythm after experiencing AF, suggesting its possible involvement in the development of AF.

In many of reports on horses with AF, certain abnormalities were observed during or after exercise, and later electrocardiographic examination showed the occurrence of AF. However, there have been few reports on ECG analysis during exercise while AF is developing. Hiraga and Kubo [22] reported 3 episodes of recording ECG at the moment when AF developed during exercise. The common ECG finding in these 3 episodes was a series of several premature contractions, suggestive of premature atrial contractions, occurring just before the onset of AF. These arrhythmias perhaps worked as a trigger to decrease the R-R intervals and increase heart rate. Moreover, AF developed when the R-R interval was reduced to 0.20 sec, 0.16 sec, and 0.19 sec during 3 episodes, respectively. Senta et al. [73] and Senta and Kubo [74] reported that AF was induced in horses following paired electrical stimulation at intervals of 0.14–0.42 sec or following repeated stimulation at similar intervals.

Paroxysmal AF was also observed in newborn foals. Machida et al. [36] reported 3 cases of paroxysmal AF among 20 newborn Thoroughbred foals they investigated, and suggested that excessive vagal tone, stretching of the atrial myocardium, and hypoxia that occurred transiently in newborn foals immediately after delivery might be predisposing factors for the onset of AF.

Chronic AF was recorded in the longest-living Thoroughbred horse in Japan [34]. The horse, named Shinzan, was the first post-war Japanese Triple Crown winner and died in July 13, 1996, at the age of 35 years and 3 months. An irregular cardiac rhythm suggestive of AF had been detected by auscultation, and the first ECG recorded in December 1994 showed that the arrhythmia was AF. Atrial fibrillation was still present in the final ECG recorded by a Holter monitor in May 1996. Therefore, Shinzan was considered to have suffered from chronic AF.

**Recording and Analysis of ECGs during Exercise**

Matsuba and Shimamura [37] measured a total of 20 physiological parameters during pre- and postexercise periods and the recovery process after exercise to evaluate the fitness of Thoroughbred racehorses by calculating the recovery rate. They published a research report entitled “Studies on exercise physiology and performance test of the racehorse” in 1933. This report was epoch-making and the most important study in the history of equine exercise physiology in Japan. As one of the parameters studied, pulse rate immediately after exercise was measured by auscultation (Fig. 10). Since direct measurement of HR during exercise was impossible at the time, pulse rate immediately after exercise was considered to indicate HR during exercise. Later, Tatsumi et al. [77] showed there was a close relationship between oxygen consumption of horses during exercise measured by the Douglas-bag method and the pulse rate immediately after exercise. Researchers then recognized the importance of HR measurements during exercise and began developing methods for measuring HR during exercise. Although it was necessary to record an ECG during exercise in order to calculate HR, it was difficult to obtain an ECG during exercise, although it could be recorded at rest.

In 1960, Nomura and Tominaga [53] recorded ECGs from a horse walking on a specially constructed treadmill at a speed of 70 m/min drafting 5 different weights (1/15, 1/10, 1/8, 1/6.5 and 1/5 of its body weight). Electrodes were placed on the withers and at the point of intersection between the center axis of the sternum and a line perpendicular to the withers. The ECGs were obtained by transmitting the signal to a receiver using a 20 MHz carrier wave and reproducing the signal with an electromagnetic oscillograph. Changes in HR during exercise and the recovery period were calculated by creating diagrams of R-R intervals from the ECG recording. Heart rate increased immediately just after the horse started exercising and came to steady-state within a short time when the workload was light. Even when the workload was heavy, the heart rate came to steady-state within 3 min, and a second increase in HR occurred about 10 min after the beginning of exercise. They pointed out that the HR response did not correlate directly with the different
Fig. 10. Changes in pulse rate before (Pre), immediately after (Post), and during the recovery process (1 hr, 2 hr, and 3 hr) after exercise. The authors drew this graph using data from a table in Matsuba and Shimamura (1933).

amount of workload weight. They demonstrated that the ECGs of a horse with an intermittent pulse had a P wave but no QRS complex or T wave and that the intermittent pulse disappeared with the start of exercise.

Although the recording of an ECG from a horse exercising on a treadmill had become possible by using a transmitter set near the horse and a carrier wave, it was still very difficult to record the ECG of a horse exercising under field conditions. Nomura stated in his research report [56] that Vasiliev of the Soviet Union had succeeded in recording ECG with radiotelemetry in 1961, and Nomura himself employed a radiotelemetry system to record the ECG of an exercising horse and rider and reported his preliminary results at a Japanese symposium on radiotelemetry held in 1962. Since this radiotelemetry system was very expensive, there was only one other system for use in a research facility at that time in Japan. Accordingly, Nomura developed a beat meter to measure the HR of draft horses during heavy pulling work at slower speeds in the field [56]. Although this device could not record the raw ECG, it enabled HR to be measured by counting pop sounds per unit time that were created when the meter detected larger amplitude signals in the ECG, e.g., the QRS complex.

A research project to record equine ECGs during exercise using radiotelemetry was performed as a collaborative study between Nomura of the University of Tokyo and the Equine Health Laboratory of the Japan Racing Association, with the results reported by Nomura et al. in 1964 [54, 55]. For the research study, a custom-made radiotelemetry system that could record ECG within 100 m was newly constructed, and the performance of the system was evaluated. A 2-cm circular silver plate with a double layer rubber cap filled with electrode paste was used as an improved electrode to reduce noise caused by exercise. Electrodes were placed on the withers and the posterior region of the saddle girth on the center axis of the sternum. The grounding electrode was placed near the hip cross. In this study, methods for recording human ECGs during exercise were also utilized to evaluate changes in HR of riders during riding.

During exercise, from walking to intense galloping, relatively clear ECGs that could be analyzed for changes in ECG waveform were obtained. However, slight deflections of the ECG waveform and contamination of electromyogram signals were observed during exercise except at a walk. These findings indicated that the new system’s electrodes and method of attaching the electrodes might need improvement. However, the researchers concluded that ECGs obtained by this system were clear enough to calculate HR or R-R intervals during exercise.

ECGs during both low-intensity exercise at a horse riding ground or low hurdle jumping and high-intensity sprint-galloping at a track were recorded by using the newly developed system in order to analyze changes in ECG waveforms and HR during exercise. The major findings obtained were as follows: 1) Characteristic findings of ECG waveforms during exercise were ST segment elevation and T wave augmentation. 2) During low-intensity exercise including walking, trotting, cantering, and extended cantering, HR increased from 45 beat/min during the pre-exercise period to 150 beat/min at an extended canter. 3) HR increased to 200 beat/min or more in most horses during 100 m high-intensity sprint-galloping. When HR increased to 200 beat/min, fusion of the T wave and the P wave was observed. The ECGs reported in this study by Nomura et al. in 1964 [55] were the first to be reported that had been measured during field exercise in the horse (Fig. 11). A similar report by Nomura was also published in 1966 in another journal [57]. Following Nomura’s publications, Holms et al. in 1966 [23] and Banister et al. in 1968 [16] reported ECGs measured during exercise in horses.

Although radiotelemetric electrocardiography during exercise in horses was introduced by Nomura et al. [54, 55, 57], it was still difficult to record the ECG of a horse exercising on a large racetrack because of the use of a low-power telemetric transmitter in that system. In order to carry out reliable recording of an ECG during exercise for a horse running on large track, a high-power telemetric transmitter was made on special order and operated under a license from the Radio Regulatory Bureau [13]. Because the high transmitting power of 1 W enabled an effective transmission range of 5 km or more, it became possible to record ECGs of horses exercising in large areas, e.g., on an oval track at a racecourse.

The results of exercise electrocardiography performed on 124 horses using this system [15] found that premature ventricular contractions were observed in 64 horses (51.6%). Among these 64 cases, 45 cases developed during the cooling down phase within 3 min after completion.
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of galloping, and 36 cases occurred within 1 min after completion of galloping. Reproducibility of monostotic premature ventricular contractions in the second or additional electrocardiographic examinations was lower, while reproducibility of consecutive or short run types of premature ventricular contractions was higher. Senta et al. [71] also reported that one episode of premature ventricular contraction during galloping and 4 episodes during cooling down after galloping were observed among 24 horses when ECGs were recorded using radiotelemetry during exercise at the Ohio State University in 1970.

In terms of ECGs during exercise, ECGs of stallion during mating were also recorded by Too et al. [82] and Hatazoe et al. [20]. Too et al. obtained ECGs from a Percheron and a Thoroughbred stallion by radiotelemetry and observed HR transiently increasing to 150–170 beat/min in the Percheron and 130 beat/min in the Thoroughbred. Premature ventricular contractions were detected during mating in the Percheron. Hatazoe et al. recorded ECGs from 10 Thoroughbred stallions using a Holter ECG system. The maximum HR during mating was 168.9 ± 14.2 beat/min, and premature ventricular contractions were observed in 3 stallions.

Although it is said that cardiac sudden death may be triggered by cardiac arrhythmias, there have been few reports on it. Kiryu et al. [27] reported 440 sec of ECG recording just before cardiac sudden death in a 2-year-old Thoroughbred racehorse following daily exercise. The ECG tracing showed that an R wave occurred on a T wave after a pair of premature ventricular contractions, and this induced ventricular fibrillation.

Although it had become possible to observe instantaneous changes in ECG during exercise by using radiotelemetry, this system had certain disadvantages; for example, it could only be used for a single horse during measurements and could only be used within the effective transmission area of a radio wave. Therefore, a portable electrocardiograph with a magnetic tape recording system for exercising horses was devised [7]. The first unit consisted of a prototype electrocardiograph, a tape recorder, and playback equipment. After several improvements, portable magnetic tape electrocardiographs became available for recording ECGs during exercise. Because the portable magnetic tape electrocardiograph allowed recording of ECGs from many horses exercising simultaneously, it became a useful tool for evaluating equine arrhythmias and HR during exercise tests performed at large racetracks. Later, a new electrocardiograph using a microcassette tape was developed (Fig. 12). This allowed simultaneous recording of 90 min of ECG and audio through 2 channels [28]. A quartz oscillator generated square pulses on the audio channel every 10 sec to correct for speed irregularities of the tape. The previously mentioned ECG recorded at the onset of AF [22] was recorded using this system. After introduction of the portable cassette tape Holter ECG system, this system became the most widely used approach. Currently, digital Holter ECG systems are widely used for exercise electrocardiography in racehorses.
**ECG Recording during Gestation and Growth**

According to an article by Okajima [63], a well-known human ECG researcher, Mito reported at the annual conference of the Japanese Circulation Society in 1970 that the equine ECG obtained by the lead method corresponds to that obtained via Lead II used in humans and that the characteristics of the equine ECG were very different from those of humans. The differences between human and equine ECGs reported by Mito served as a starting point, and the Japanese Society of Comparative Electrocardiography was established in 1974 to discuss ECGs of both humans and animals, especially those of the horse, from the viewpoint of comparative electrocardiography. Discussions at annual meetings have contributed greatly to development of both equine and human electrocardiography.

Comparative studies of equine ECGs, including ponies, and ECGs of other animals, e.g., cattle, pigs, goats, and chickens, have been studied intensively [39, 40, 45, 46]. Moreover, studies on changes in the fetal ECG during pregnancy and changes in ECG during development in Thoroughbred foals after birth have been reported [39, 40, 42, 43]. Studies on how values of electrocardiographic parameters change with growth have been evaluated in Thoroughbred horses [39]. ECGs obtained by the AB lead and the standard limb leads were recorded over the period from 1 week to 12 months after birth. The RR, PQ, and QT intervals, and the P and QRS durations prolonged distinctly with growth. The deflections of the QRS wave were generally bimodal, and their amplitudes were about 0.2 mV for 12 months after birth. The deflections of the QRS wave complex were observed as rS or QS types in all cases. The deflection of the T wave showed characteristic changes with increased growth. It showed a negative or a predominantly negative pattern at a few days of age, a predominantly positive pattern for the following 30 days, and again a negative or predominantly negative one after 2 months of age.

Electrocardiograms from fetus to foal were recorded chronologically in 10 cases from 190 days gestation onward and from a few days after delivery until 12 months after birth [40]. In this study, fetal HR progressively decreased with the advance in gestation. After birth, the HR increased to a much higher value than at the end of gestation, but then started to decrease and gradually reached adult values at about 4 to 5 months of age.

In another study [42], fetal ECGs were recorded from 10 pregnant Thoroughbred mares throughout gestation from 6 months onward in order to observe changes in baseline fetal HR and fetal HR acceleration. Baseline fetal HR was defined as the mean of fetal HR for 5 min when fetal HR was most stable during measurement, while fetal HR acceleration was defined as a period in which a transient increase in HR was observed. In this study, it was demonstrated that the baseline fetal HR decreased in a logarithmic manner with the advance in gestation period, while the maternal HR increased over the same period. The frequency and magnitude of fetal HR acceleration increased during the latter period of gestation, suggesting the development of fetal body movement.

A fetal ECG in the twin pregnancy of a Thoroughbred has also been recorded [43]. One colt was born healthy, but the other colt was born growth retarded. Fetal HR in both colts decreased similarly with the advance in gestation, with a higher HR obtained from the growth retarded colt. Maternal HR increased gradually with the advancement of gestational period and then increased prominently during the last 2 weeks before parturition. By performing these studies, the characteristics of the ECG during growth from fetus to newborn foal in Thoroughbred horses have been elucidated.

**Conclusions and Future Study**

Because the Thoroughbred racehorse is considered to be an elite athlete, it is unlikely that racehorses suffering from heart disorders have been common in horse racing. Therefore, the main objective of electrocardiography as applied to racehorses is one of routine medical examination rather than diagnosing severe heart disease. In the case of AF that occurs in races, electrocardiography both at rest and during exercise has been performed by the Japan Racing Association and clarified a number of issues related to this arrhythmia.

In contrast, Thoroughbred stallions are considered important candidates for electrocardiography both at rest and during exercise because cardiac sudden deaths are observed during mating and daily exercise [21]. Breeding stallions are usually older, 10-year-old or, in some cases, over 20-year-old. It is assumed that cardiac function of older stallions, including autonomic nervous function, differs from that of younger horses. Although it might be considered that changes in cardiac function accompanying aging might impact the occurrence of heart disease, there are few data available on basic physiological changes in cardiac function of the horse that occur with aging.

Kuwahara et al. [33] established a new method for evaluating autonomic nervous function of Thoroughbred horses by applying power spectral analysis of heart rate variability. Thereafter, many papers have been published using this method on topics as diverse as effects of training [35, 60], evaluation of drugs [59, 61], effects of transport [62], and effects of immersion in hot spring water [26] as a
result of collaborative studies between the Equine Research Institute of the Japan Racing Association and the University of Tokyo.

In recent years, advances in human medicine have opened new approaches for evaluating cardiac function (e.g., tone entropy method, measurement of ventricular mini-potentials, etc.), including autonomic nervous function, although these methods have not been reported for use in equine medicine. Application of these methods to horses has the potential to further new developments in equine electrocardiography and contribute to improving the health and welfare of the horse.

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References


