Changes in Cardiac Output with Experimentally Induced Atrial Fibrillation in the Horse

Katsuyoshi KUBO*, Tetsuo SENTA* and Osamu SUGIMOTO*

Cardiac output was determined in 7 horses before and after conversion from sinus rhythm to experimentally induced atrial fibrillation. The right atrium was stimulated repeatedly by electric current via a cardiac catheter for 15 to 20 seconds. Atrial fibrillation was successfully induced in all the horses without visible signs. Cardiac output showed a striking increase in 2 horses, a slight increase in three, and a slight decrease in two. The average increase was 12 per cent.

The heart rate increased significantly in all the horses. The average increase was 43 per cent. Consequently, the stroke volume decreased significantly in all the horses after the conversion. The average decrease was 22 per cent of the pre-conversion value.

Introduction

Atrial fibrillation is said to be a dysfunction of the heart in which the atria fail to contract as a whole and lose their pumping action. Reports have frequently been made on atrial fibrillation in the horse since Lewis.1) Most of them, however, deal with the clinical observation, electrocardiography, and treatment of this disorder.

The hemodynamics of atrial fibrillation has been studied by a large number of investigators in human beings, while information on it in the horse is quite limited. Detweiler and Patterson2) described that some horses with atrial fibrillation would hardly give any evidence of cardiac disability if the heart rate was low at rest, but that they had invariably reduced stamina and limited ability to perform strenuous work. Clinical experience also revealed that the underlying heart disease was less severe in the horse than in the dog. In human beings, Grant et al.3) reported that average energy loss to ventricular filling in atrial fibrillation was 16 per cent. It is questionable whether the hemodynamics of atrial fibrillation in the horse is quite similar to that in man or any other animal.

Cardiac output was determined before and after conversion from sinus rhythm to atrial fibrillation. The purpose of this paper is to describe changes in cardiac output with experimental conversion from sinus rhythm to atrial fibrillation induced by electrical stimulation in the horse.

Materials and Methods

Experimental animals Seven horses were used in this study. They were
Thoroughbred males from 3 to 6 years of age weighing 398 to 467 kilograms, and free from the clinical and electrocardiographic evidence of cardiovascular disease. Each animal was held in the fasting state since the night before the experiment. During the experiment, it was allowed to stand quietly in the stocks without administration of any sedative, anesthetic, analgesic or other drug.

Induction of atrial fibrillation A cardiac catheter was inserted into the right atrium via the jugular vein. The method of repeated stimulation by electric current reported by Senta et al. was applied through the catheter to induce atrial fibrillation; that is, the right atrium was paced with impulses 10 volts in amplitude, 0.01 second in duration and 200 to 240 per minute in frequency for 15 to 20 seconds.

Measurement of cardiac output Cardiac output was determined by the dye dilution method using the technic previously reported by Kubo et al. The stroke volume was calculated by dividing cardiac output by heart rate. The first measurement of cardiac output was done during the stage of sinus rhythm as the resting value in 7 horses (control). The second measurement was done shortly after the bout of atrial fibrillation. In four of the 7 horses the third measurement was done after a spontaneous reversion to sinus rhythm. In one of the 4 horses further measurements were done (details are described later). Bipolar chest lead electrocardiogram and phonocardiogram in the mitral area were recorded simultaneously by all the procedures mentioned above.

Fig. 1. Electrocardiogram of atrial fibrillation induced by electrical stimulation (A), and the diagram (B) and histogram (C) of heart-beat intervals (R-R intervals) derived from electrocardiographic recordings (Horse No. 4)

The number shown below the recording indicates an R-R interval expressed in terms of one-hundredth of a second. The diagram (B) presents an irregular variation of R-R intervals derived from 100 consecutive heart-beats. The histogram (C) was obtained from the values of 100 R-R intervals given in (B).
Changes in Cardiac Output with Atrial Fibrillation

Results

Atrial fibrillation was induced successfully in all the experimental animals manifesting no such visible signs as syncope, jugular pulsation, coughing, choking up, and any other agitation. It was reverted spontaneously to sinus rhythm in all the animals. Fig. 1 shows one of the electrocardiograms recorded during the period of experimentally induced atrial fibrillation, and the diagram and histogram of heart-beat intervals in horse No. 4. The electrocardiogram is characterized by the absence of P waves, the presence of f waves of varying amplitude, contour and spacing, and the presence of irregular ventricular beating. The rate of f waves during the period of arrhythmia ranged from 200 to 320 per minute in 7 horses.

Table 1 shows the results of cardiac output before and after conversion from sinus rhythm to atrial fibrillation. Cardiac output increased strikingly in 2 horses (Nos. 3 and 4) and slightly in 3 horses (Nos. 2, 6, and 7), and decreased slightly in 2 horses (Nos. 1 and 5). The average increase in cardiac output was 2.5 liters per minute following conversion to atrial fibrillation. The heart rate increased and the stroke volume decreased in all the horses. The stroke volume decreased by 226 milliliters on the average per beat, as compared with the pre-conversion value. The heart rate increased by 11 beats on the average per minute.

Fig. 2 shows changes in the cardiac output, the stroke volume and the heart rate following the establishment of atrial fibrillation as percentages to the pre-

![Graph showing changes in cardiac output, stroke volume, and heart rate before and after atrial fibrillation.]

Table 1. Details of 7 horses with experimentally induced atrial fibrillation

<table>
<thead>
<tr>
<th>Horse No.</th>
<th>Age</th>
<th>Body weight (kg)</th>
<th>Before atrial fibrillation</th>
<th>During atrial fibrillation</th>
<th>After atrial fibrillation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CO (l/min)</td>
<td>SV (ml)</td>
<td>HR</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>400</td>
<td>23.7</td>
<td>1,187</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>467</td>
<td>26.0</td>
<td>930</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>459</td>
<td>23.3</td>
<td>1,164</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>455</td>
<td>23.1</td>
<td>923</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>398</td>
<td>24.8</td>
<td>801</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>449</td>
<td>26.3</td>
<td>1,097</td>
<td>24</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>453</td>
<td>30.2</td>
<td>1,042</td>
<td>29</td>
</tr>
</tbody>
</table>

Average 25.3±2.5 1,021±142 25±4 27.8±2.5 794±157 36±8

Abbreviations. CO, cardiac output; HR, heart rate; and SV, stroke volume.
Fig. 3. Changes in cardiac output (A), stroke volume (B), and heart rate (C) before (a) and after (b) conversion of sinus rhythm to atrial fibrillation and after (c) spontaneous reversion to sinus rhythm, expressed as percentage to the pre-conversion value. The broken line shows the average value.

Fig. 4. Changes in cardiac output (CO), stroke volume (SV), and heart rate (HR) expressed as percentage to the pre-conversion value. In Horse No. 4, cardiac output was determined repeatedly during the periods of sinus rhythm and atrial fibrillation alternately. The abscissa shows the time in minutes after the first cardiac output was determined (0 minute). The broken lines on the abscissa show periods when atrial fibrillation (AF) was maintained. The blank circle shows the value during the period of fibrillation and the solid circle that during the period of sinus rhythm. Cardiac output increased by 12 per cent on the average, the decrease being significant (P<0.001).

In 4 horses cardiac output was measured after atrial fibrillation was reverted spontaneously to sinus rhythm. The reappearance of sinus rhythm was accompanied by a significant increase in the stroke volume (P<0.001) and a significant decrease in the cardiac output and the heart rate as shown in Fig. 3.

Furthermore, in one horse atrial fibrillation was induced repeatedly for 3 times. Each atrial fibrillation lasted for about 9, 17 and more than 105 minutes. Cardiac output was measured alternately during the periods of atrial fibrillation and sinus rhythm, as shown in Fig. 4. The results obtained show that the stroke volume is large during the period of sinus rhythm and small during the period of atrial fibrillation. During the period of the last fibrillation, cardiac output was measured four times, or 13, 29, 78 and 92 minutes after the bout. The stroke volume decreased gradually as the time passed.

When atrial fibrillation was induced, the phonocardiogram recorded varied in amplitude, but showed the presence of the second heart sound. No cardiac murmur was detected at any time of measurement of cardiac output.

Discussion

According to Detweiler and Patterson, the frequency of atrial oscillations ranged from 300 to 500 per minute in the equine atrial fibrillation. The rate of f (or F) wave in this study was lower than that found in clinical cases. So far as this rate is concerned, it seems impossible to decide whether the arrhythmia observed in the present investigation is fibrillation.
Changes in Cardiac Output with Atrial Fibrillation

or flutter, since no reports have ever been made on equine flutter. In man, Katz and Pick\(^6\) described that electrocardiographic diagnosis was based on the absence of P waves, the presence of irregular ventricular beating, and the presence of undulation of varying amplitude, contour, and spacing, the rate of this undulation usually ranging from 350 to 600 per minute. Aside from its low frequency in f waves, the arrhythmia in question met all the criteria mentioned above. Consequently, it was diagnosed as functional atrial fibrillation of Brooijmans' classification\(^7\) in the absence of structural heart disease.

A few workers have studied the hemodynamics of atrial fibrillation in the horse. Detweiler\(^8\) measured blood pressure in horses involved in experimental or spontaneous atrial fibrillation. He reported that blood pressure had become high in these horses, and that it was normal both before and after the bout of arrhythmia in one horse affected with paroxysmal atrial fibrillation. Amada et al.\(^9\) recorded the right atrial and carotid arterial pressure curves at rest from a horse with atrial fibrillation. They found that the right atrial pressure was abnormally high and carotid arterial pressure in a normal range. These findings seemed to show that arterial blood pressure was not in especially severe conditions. No observation has been made previously on cardiac output in atrial fibrillation in the horse.

In general, it is known in horses with atrial fibrillation that the heart loses its ability to function effectively as a pump, and that the clinical significance of atrial fibrillation depends on the severity of the underlying heart disease. It has frequently been reported that many horses with atrial fibrillation are in such benign clinical conditions that they have no visible signs of cardiac disorder at rest and are considerably tolerant to moderate exercise.\(^7,9\) The slightly poor tolerance of such horses to exercise seems to be attributable only to a hemodynamic disadvantage accompanied by atrial fibrillation. However, to what extent the lack of normal atrial contraction and the irregular ventricular rhythm affect the ability of the heart is not clear in the horse. From the viewpoint of atrial contribution to ventricular filling in the human being and experimental animals, a large number of investigators carried out studies on the effect of atrial fibrillation on the hemodynamics.

In the human being, Grant et al.\(^3\) emphasized that the left atrium had a function as reservoir and was an important factor in filling the ventricle. They also recognized that the contribution of atrial contraction was about 20 per cent. Benchimol et al.\(^15\) demonstrated that conversion from atrial fibrillation to sinus rhythm resulted in an increase in the average stroke index of 8 patients by 22 per cent.

In dogs, Mitchell et al.\(^16\) determined effective or forward ventricular stroke volumes for ventricular ejections preceded or not preceded by an atrial systole. When ventricular beats were not preceded by the atrial systole, the average drop in effective ventricular stroke volume was 20 per cent at low heart rates (60 to 90 beats/min) and 37 per cent at high heart rates (150 to 210 beats/min). In dogs, Snyder et al.\(^17\) found that the stroke volume increased by 7 to 8 per cent when an atrial systole
had been so adjusted as to occur 0.1 second prior to the closure of the atrioventricular valves, and that it decreased by a similar magnitude when the contribution of atrial systole to ventricular filling had been rendered ineffective by the use of an A-V delay of zero so that the blood of the atria might be prevented from emptying into the ventricles by the closed A-V valves. The results of the present investigation may have been influenced by both lack of atrial contraction and the occurrence of irregular ventricular rhythm.

Some cases of cardiac murmurs in atrial fibrillation were reported in horses. Holmes et al. encountered cases of 3 RAV, 3 LAV, and 4 RAV and LAV systolic murmurs when they had examined 23 horses with atrial fibrillation. The phonocardiograms recorded in this study showed no cardiac murmurs. Consequently, no cardiac output seemed to have been influenced by such factor as mitral insufficiency with regurgitation.

It is also known that cardiac output is influenced by such variables as the lapse of time between tests, metabolic condition, and heart rate. It is questionable that the tendency shown in Fig. 2 was a reflection of rhythm alone. Then, the measurement of cardiac output was repeated, as shown in Figs. 3 and 4. As is clear from Fig. 3, there is a good contrast between the changes in cardiac output, stroke volume, and heart rate after spontaneous reversion from atrial fibrillation to sinus rhythm and those after conversion from sinus rhythm to atrial fibrillation. Only one horse showed a less decrease in stroke volume than any other horse. Such factors as light heart weight (3.1 kilograms), the highest increment in heart rate, and the shortest average R-R intervals may contribute to this decrease, but no exact cause is known.

The results given in Fig. 4 show that the conversion from sinus rhythm to atrial fibrillation was accompanied by unchanged or increased cardiac output, increased of heart rate, and decreased stroke volume, and that the conversion from atrial fibrillation to sinus rhythm was accompanied by the reverse phenomena. These results seem to indicate that the results shown in Table 1 are reproducible. The stroke volume presented in Fig. 4 tends to decrease with the lapse of time and seems to suggest that some factors concerning time may be considered in clarifying the hemodynamics. When ±10 per cent was assumed arbitrarily to be a limit of significant change in cardiac output, the results of the present investigation of conversion from sinus rhythm to atrial fibrillation show an increase in cardiac output in 2 horses and unchanged cardiac output in 5 horses. The heart rate increased strikingly in 3 horses. It was accompanied by an apparent increase in cardiac output in 2 of the 3 horses, but not in the other horse. In 7 horses cardiac output increased by 12 per cent on the average. This increase was surpassed by that in heart rate, and not significant (P<0.1).

Consequently, the stroke volume decreased significantly in all the horses. It decreased by 22 per cent, on the average, of the pre-conversion value.

With reversion from atrial fibrillation to sinus rhythm, cardiac output showed no changes or a mild increase in human beings. With conversion from sinus rhythm to atrial fibrillation, cardiac output
showed a contrasting tendency in horses in the present investigation.

It is suggested from this investigation that the tendency of cardiac output to increase may be attributable to a more marked increase in heart rate than decrease in stroke volume due to the lack of atrial contraction and irregular ventricular rhythm.

Acknowledgments

The authors wish to thank Dr. A. Amada, of the Equine Health Laboratory, Japan Racing Association, for his guidance. They are also grateful to Miss K. Nishimoto, of the same laboratory, for her technical assistance.

Literature Cited

K. Kubo, T. Senta and O. Sugimoto

馬の実験的心房細動発症にともなう心拍出量の変化について

久保勝義*・千田哲生*・杉本 修*

7頭の馬を使用して実験的に心房細動を発生させ、
洞リズムから心房細動への転換の前後に於ける心拍出
量の変化を測定した。

心臓カテーテルを右心房腔に挿入し、それを経由し
て、電圧 10V，持続時間 0.01 秒の電気刺激を 1 分間
200 ないし 240 の頻度で約 20 秒間負荷した。その結果、
観察上、認めべき変化もなく、すべての馬に心房細動
を発生させることができた。

毎分拍出量は、2頭において著しい増加、3頭にお
いてわずかな増加、2頭においてわずかな減少を示し
た。心拍数は、すべての馬において有意に増加した。
その平均増加率は 43% であった。

平均毎分拍出量の増加率は 12% で、心拍数の増加
に比べ 31% 低く、有意な変化ではなかった。したが
って、1回拍出量は、すべての馬において有意に減少
した。洞リズムのそれに対する減少率の平均は 22%で
あり、心臓収縮の効率の低下を示した。