

CARDIOVASCULAR CHANGES IN THE EXERCISING EMU

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SUMMARY

Cardiovascular variables were studied as a function of oxygen consumption in the emu, a large, flightless ratite bird well suited to treadmill exercise. At the highest level of exercise, the birds' rate of oxygen consumption (\dot{V}_{O_2}) was approximately 11.4 times the resting level ($4.2 \text{ ml kg}^{-1} \text{ min}^{-1}$). Cardiac output was linearly related to \dot{V}_{O_2} , increasing 9.5 ml for each 1 ml increase in oxygen consumption. The increase in cardiac output is similar to that in other birds, but appears to be larger than in mammals. The venous oxygen content dropped during exercise, thus increasing the arteriovenous oxygen content difference. At the highest levels of exercise, heart rate showed a 3.9-fold increase over the resting rate ($45.8 \text{ beats min}^{-1}$). The mean resting specific stroke volume was 1.5 ml per kg body mass, which is larger than shown by most mammals. However, birds have larger hearts relative to body mass than do mammals, and stroke volume expressed per gram of heart (0.18 ml g^{-1}) is similar to that for mammals. Stroke volume showed a 1.8-fold increase as a result of exercise in the emus, but a change in heart rate plays a greater role in increasing cardiac output during exercise.

INTRODUCTION

Birds have larger hearts than mammals of similar body mass (Lasiewski & Calder, 1971), and it is of interest to determine what role this larger heart may play in meeting the increased demand for oxygen during vigorous exercise.

Several studies have been published on cardiovascular changes associated with exercise in birds (see Butler, West & Jones, 1977; Kiley, Kuhlmann & Fedde, 1979; Bech & Nomoto, 1982; Grubb, 1982*a*). While these studies have looked at \dot{V}_{O_2} during resting and exercise (up to 10 times resting value, Butler *et al.* 1977), none has investigated metabolic and cardiovascular changes over a range of exercise levels from very moderate to heavy exercise. This is mainly because of (i) the technical difficulties involved in windtunnel flight studies, and (ii) the inability of the birds thus far studied to run at high speeds for prolonged periods on a treadmill. We studied cardiovascular changes in the emu because this flightless bird is adapted for running, whereas other birds that have been studied during treadmill exercise are not.

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MATERIALS AND METHODS

Two, 24-month-old adult emus (*Dromiceius novaehollandiae*) with a mean body mass of 37.5 kg were used in this study. The birds were kept in a large outdoor enclosure with a sand floor and had free access to a pool of fresh water and a supply of poultry chow, lettuce and apples.

Measurement of oxygen consumption

Oxygen consumption was measured using an open system similar to that previously described by Grubb (1982a). The emus wore a rubber mask and room air was pulled past the face at a rate of 140 l min⁻¹. This flow rate was found to be adequate to capture all expired gases during both rest and exercise. The mask was made by brushing repeated layers of rubber latex onto a clay mould the size and shape of the bird's head, leaving holes for eyes and beak. A plastic cone with a connector for a suction hose was made to fit over the exposed beak and attach to the mask. When oxygen consumption was being measured, the suction hose was attached to the cone to collect the expired air.

An electronic flowmeter (Matheson, East Rutherford, N.J.) was placed downstream of the mask so that the flow through the mask could be measured continuously. After passing through the flowmeter, a portion of the expired air was dried by freezing the water out of the airstream in an alcohol bath at -70°C, and the gas stream was then passed through an oxygen analyser (Applied Electrochemistry, Sunnyvale, CA) and an infrared CO₂ analyser (Lire, Pittsburgh, PA). (For additional information on instruments, calibration, etc. see Grubb, 1982a.) The voltage output from the flowmeter and the O₂ and CO₂ analysers was digitized and recorded on magnetic tape at 1 min intervals throughout the experiment. The magnetic tape was then fed into a computer which was programmed to calculate oxygen consumption according to equation (2) given by Tucker (1968).

Cardiac output

Cardiac output was derived from the arteriovenous content difference and measured \dot{V}_{O_2} using the Fick principle: $\dot{V}_{O_2} = \dot{Q}(C_{a,O_2} - C_{\bar{v},O_2})$, where \dot{V}_{O_2} is the rate of oxygen consumption (STPD), \dot{Q} is the cardiac output, and $C_{a,O_2} - C_{\bar{v},O_2}$ is the arteriovenous oxygen content difference.

Blood sampling

Arterial and venous blood samples were drawn through cannulae (PE 90) placed in the brachial artery and right ventricle (via the brachial vein). Before the cannulation surgery, the bird was anaesthetized with Ketamine (see Grubb, 1982b) and the cannulae were coated with TDMAC Heparin (Polysciences, Inc., Warrington, PA). Correct placement in the right ventricle was assured by observing the change in venous pressure as the cannula was threaded through the brachial vein toward the heart. Both cannulae were connected to Statham pressure transducers which in turn were connected to a two-channel Brush recorder (Gould, Cleveland, OH). Between sampling periods the cannulae were filled with heparinized saline (100 μ l ml⁻¹).

The paired blood samples (arterial and venous) were drawn within a few seconds of each other and were immediately analysed for oxygen content using a Lex-O₂-Con (Lexington Instruments, Waltham, MA). Each sample (0.5 ml) was analysed in duplicate and the two determinations were then averaged. Blood samples were drawn only when the rate of oxygen consumption was in a steady state (i.e. \dot{V}_{O_2} changed no more than 5% during a 10 minute period). Over a 2 week period, approximately 30 paired samples (30 ml blood) were taken from one bird and 60 paired samples (60 ml blood) from the other bird. Neither of the birds showed a significant decrease in haematocrit.

Training the birds

Emus are large and powerful animals and difficult to handle, particularly when they are frightened by novel situations and surroundings. Therefore, an extensive training period was employed to familiarize the birds with the breathing apparatus and the treadmill (Collins, Braintree, MA). The latex mask was put on the birds daily for several months prior to the experiments. By the end of the training period the birds ignored the mask when it was in place. Each bird received treadmill training for short periods (about 10 min) once or twice per week for several months prior to the experiments. The birds usually ran well at slow speeds but became excited and unpredictable when the speed of the treadmill was increased much beyond 1.33 m s^{-1} . While emus are capable of running much faster than this, the artificial situation on the treadmill seemed to cause the bird problems at the higher speeds. Therefore, in order to increase the bird's metabolic rate, it was necessary to incline the tread.

During the resting measurements the bird was kept in a large wooden box ($1.25 \times 0.70 \times 1.35 \text{ m}$) and would often lie down and sleep during measurements. No resting data were taken when the bird was on the treadmill. A large cage ($0.9 \times 1.5 \times 1.6 \text{ m}$) was built over the tread to keep the bird confined while running. During the experiments the tread speed ranged from 0.53 m s^{-1} to 1.33 m s^{-1} , and the tread angle from 0 to 6 degrees. Each bird ran on the treadmill for 20–25 min during each data collection period. It was then allowed to rest for 4 h before being run a second time that day. The duration of the study was about 10 days for each bird.

RESULTS

The mean resting rate of oxygen consumption and the resting cardiovascular variables for the two emus are shown in Table 1. As further studies were planned for the two trained emus, the heart weight was determined from a third emu of the same body mass as the two used in the present investigation. Also included in Table 1 is the highest recorded \dot{V}_{O_2} with the corresponding heart rate and cardiac output at this level of exercise (tread speed 1.33 m s^{-1} , 6° incline).

The cardiac output increased with the rate of oxygen consumption (Fig. 1). A linear regression was run on the data (method of least squares) and this relationship is represented by the linear equation $Y = 33.25 + 9.53X$, where Y is weight specific cardiac output in $\text{ml kg}^{-1} \text{ min}^{-1}$ and X is weight specific \dot{V}_{O_2} in $\text{ml kg}^{-1} \text{ min}^{-1}$. Data both resting and exercising birds are shown in Fig. 1.

Table 1. *Body and heart weights, $\dot{V}O_2$, and cardiovascular variables in emus at rest and at the highest level of exercise*

| | Rest | Highest level of exercise |
|---|------------------------------|---------------------------|
| Mean body mass (kg) | 37.5 (2) | — |
| Heart mass (g) | 319 (1) | — |
| $\dot{V}O_2$ (ml kg ⁻¹ min ⁻¹) | 4.18 ± 1.16 (17) | 48.2 (2) |
| Cardiac output (ml kg ⁻¹ min ⁻¹) | 67.9 ± 15.2 (17) | 494 (2) |
| Heart rate (beats min ⁻¹) | 45.8 ± 5.12 (17) | 180 (2) |
| Blood pressure (mmHg) | 149.3/116.2 ± 14.4/18.4 (17) | 165/111 (2) |
| Stroke volume (ml kg ⁻¹) | 1.52 ± 0.61 (17) | 2.74 (2) |

Mean ± s.d. are shown with the number of determinations in parentheses.

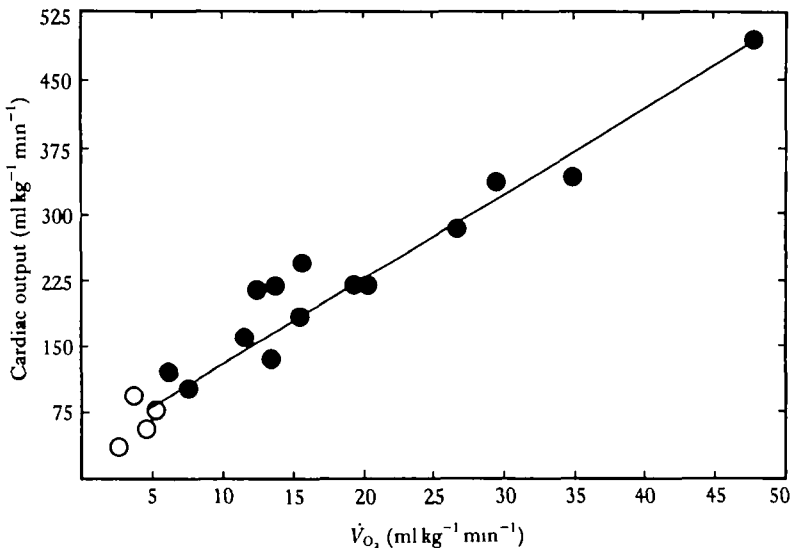


Fig. 1. Relationship between cardiac output and oxygen consumption in emus. Each point on this and the following graphs is a mean of 2–5 samples taken during an individual run on one bird. There was no systematic difference in the data between the two birds, thus the data for both birds are analysed together. The resting data are shown as open circles; the exercise data as closed circles. The linear equation is $Y = 33.25 + 9.53X$, where Y is weight specific cardiac output in ml kg⁻¹ min⁻¹ and X is weight specific $\dot{V}O_2$ in ml kg⁻¹ min⁻¹. (All measurements taken at STPD.)

The relationship between the arterial and venous oxygen content of the blood and the rate of oxygen consumption is shown in Fig. 2. The mean arterial oxygen content was 15.12 ± 0.86 vol % (haematocrit 35.9%). The mean venous content during rest was 8.99 vol % (± 1.80 s.d.) and it decreased to approximately 4.6 vol % at the two highest levels of exercise.

Heart rate increased as the $\dot{V}O_2$ increased, $r = 0.97$, $P < 0.01$ (Fig. 3). Heart rate increased from a mean resting value of 45.8 ± 5.1 to 180 beats min⁻¹ at the highest $\dot{V}O_2$ (48.2 ml kg⁻¹ min⁻¹).

The mean resting specific stroke volume for the emus was 1.52 ml kg⁻¹. Stro

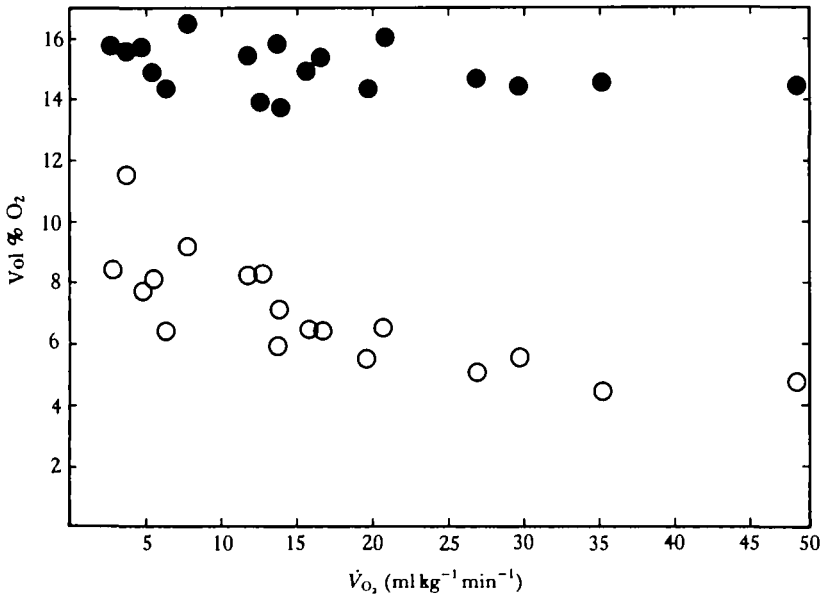


Fig. 2. Relationship between the arterial and venous oxygen content and the rate of oxygen consumption in two emus. Arterial blood oxygen content is shown as closed circles and venous blood oxygen content as open circles.

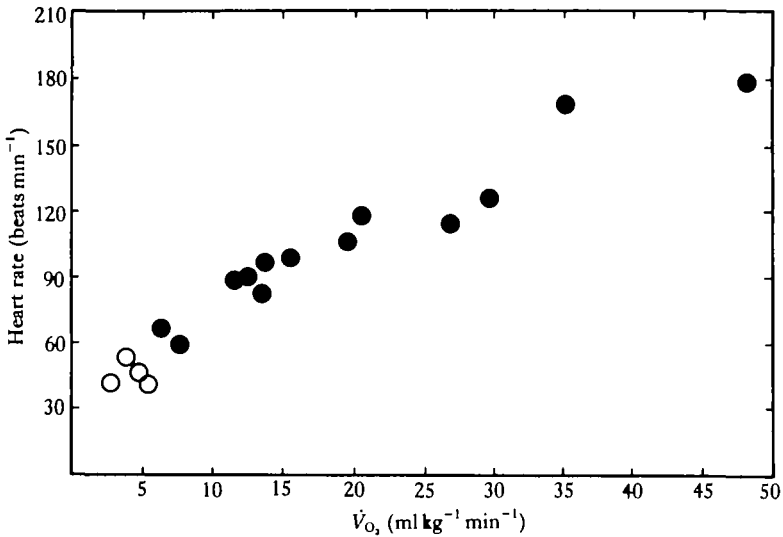


Fig. 3. Relationship between heart rate and the rate of oxygen consumption in two emus. Resting data are shown as open circles.

volume increased significantly as the birds' rate of oxygen consumption increased, $r = 0.67$, $P < 0.05$ (Fig. 4).

Resting blood pressure is shown in Table 1. Exercise had no significant effect on blood pressure. The mean blood pressure during exercise (all exercise values pooled) was 153/111.5 (12.5/11.0 s.d.), $n = 14$.

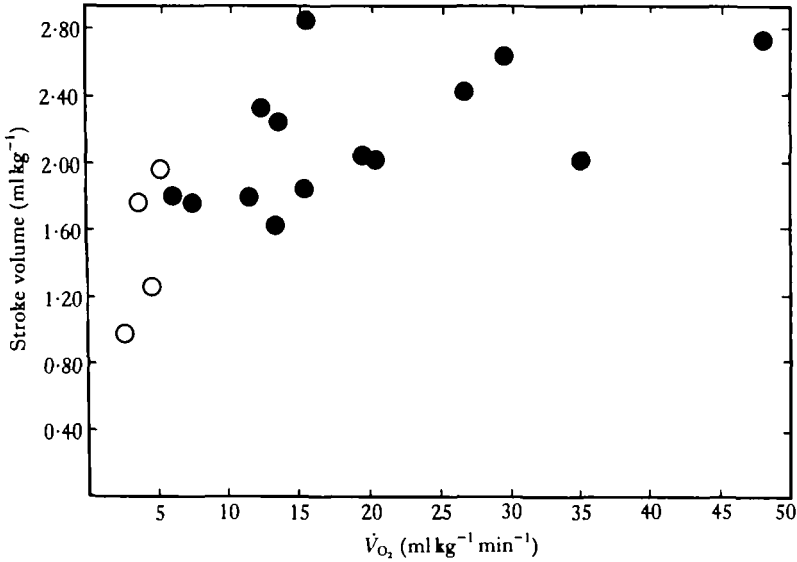


Fig. 4. Relationship between stroke volume and the rate of oxygen consumption in two emus. Resting data are shown as open circles.

DISCUSSION

There are very few studies in the literature on cardiovascular performance in birds during exercise and there do not appear to be any studies in which the cardiovascular system was studied over a continuous range of oxygen consumption from rest up to the levels of oxygen consumption during flight (10 times rest or more). This is in part because the treadmill studies done thus far have used birds which are ordinarily flyers or swimmers (pigeons, ducks) rather than runners (Kiley *et al.* 1979; Bech & Nomoto, 1982; Grubb, 1982a), and because windtunnel studies are technically difficult and do not yield intermediate values between rest and flight (Butler *et al.* 1977).

The emu was chosen for this study because it is a fast running terrestrial bird, well adapted to treadmill exercise, and it is large enough to allow repeated blood samples to be taken.

In exercising emus, we measured \dot{V}_{O_2} greater than 10 times resting values. The birds did not appear to be stressed while running and are capable of running much faster than they ran on our treadmill. Thus their maximal \dot{V}_{O_2} is probably well above the highest level of oxygen consumption we recorded.

Cardiac output was linearly related to oxygen consumption, as it has been found to be in ducks and pigeons (Grubb, 1982a) and dogs (Barger, Richards, Metcalfe & Günther, 1956). The slope of the line relating cardiac output to \dot{V}_{O_2} in emus was 9.5, indicating that cardiac output rose 9.5 ml for each 1 ml increase in \dot{V}_{O_2} . This slope is almost identical to that for ducks and pigeons (Grubb, 1982a), but it appears to be higher than that reported for mammals (Barger *et al.* 1956). (See Grubb, 1982a for a discussion.)

As the rate of oxygen consumption increased, the venous oxygen content dropped. This same general relationship was found for ducks, pigeons (Grubb, 1982a) and dogs (Barger *et al.* 1956). There was an increase in the mean resting arterioveno

oxygen content difference from 6.7 vol % at rest to 10 vol % at the highest level of exercise ($\dot{V}_{O_2} = 11.4$ times rest).

The mean O_2 content difference at rest (6.7 vol %) is somewhat higher than values obtained for ducks (4.5 vol %) and pigeons (5.02 vol %) (Grubb, 1982a). Also, the dog's resting $C_{a,O_2} - C_{\bar{v},O_2}$ is approximately 5 vol % (Barger *et al.* 1956). Untrained man appears to have a resting $C_{a,O_2} - C_{\bar{v},O_2}$ in the range of 4.3–5.5 vol % (Musshoff, Reindell & Klepzig, 1959; McDonough & Danielson, 1974). However, it is interesting that trained athletes had a resting O_2 content difference (6.5 vol %) larger than that of untrained man (Musshoff *et al.* 1959), and similar to the value we found in emus.

The increase in $C_{a,O_2} - C_{\bar{v},O_2}$ at the highest level of exercise in the emus seems quite modest when compared to mammals (Table 2). Also, pigeons at high levels of exercise (Butler *et al.* 1977) do not appear to show the magnitude of $C_{a,O_2} - C_{\bar{v},O_2}$ increase shown by mammals. In emus, the venous oxygen content reached 4.4 vol % at the higher levels of exercise. Butler *et al.* (1977) found that pigeon blood contained 5.4 vol % O_2 at high levels of exercise. These two avian species show venous O_2 content levels similar to that seen in mammals during strenuous exercise (Barger *et al.* 1956; McDonough & Danielson, 1974).

The arterial oxygen content in man and dogs averages between 18 and 20 vol % (Barger *et al.* 1956; McDonough & Danielson, 1974), whereas the oxygen content of the emu's blood was 15.12 vol % (13.7–15.1 vol % in pigeons; Butler *et al.* 1977). Since the maximum $C_{a,O_2} - C_{\bar{v},O_2}$ will depend on the oxygen content of the arterial blood, it follows that emus (as well as other avian species studied, Butler *et al.* 1977; Grubb, 1982a) will have a lower $C_{a,O_2} - C_{\bar{v},O_2}$ during exercise. A lower arteriovenous oxygen content difference in these birds would necessitate a higher cardiac output, compared with that of mammals, in order to deliver a given amount of oxygen (assuming differences in oxygen dissociation curves are relatively unimportant).

Heart rates increased as the rate of oxygen consumption increased, with about a four-fold increase at the highest rates of oxygen consumption. It is doubtful that this is the maximal factorial increase in heart rate attainable by these birds. The heart rate of a pigeon in flight has been measured to be about 5.8 times the resting level (Butler *et al.* 1977). The barnacle goose in flight has a heart rate of about 7.24 times rest, which is considered to be maximal (Butler & Woakes, 1980). Humans undergoing maximal exertion usually show about a three-fold increase in heart rate over rest (Musshoff *et al.* 1959; Astrand, Cuddy, Saltin & Stenberg, 1974). Exercising dogs

Table 2. Comparison of \dot{V}_{O_2} and $C_{a,O_2} - C_{\bar{v},O_2}$ in different species during strenuous exercise

| Animal | \dot{V}_{O_2} (times resting level) | $C_{a,O_2} - C_{\bar{v},O_2}$ (times resting level) |
|---|--|--|
| Emu (this study) | 11.4 | 1.48 |
| Pigeon (Butler <i>et al.</i> 1977) | 9.85 | 1.80 |
| Dog (Barger <i>et al.</i> 1956) | 10.4 | 2.38 |
| Pig (calculated from Hastings <i>et al.</i> 1982) | 8.82 | 3 |
| Untrained man (McDonough & Danielson, 1974) | 11.3 | 3.35 |
| Untrained man (Musshoff <i>et al.</i> 1959) | 6.48 | 2.36 |
| Athletes (Musshoff <i>et al.</i> 1959) | 7.83 | 2.32 |

and pigs have a 3.2- and 3.26-fold increase, respectively, in heart rate over the rest rate (Hastings, White, Sanders & Bloor, 1982).

The mean resting specific stroke volume (1.5 ml kg^{-1}) in emus is similar to that found in ducks, but lower than in pigeons (Grubb, 1982a). This weight-specific stroke volume is larger than reported for a wide range of mammals (0.92 ml kg^{-1}) (Holt, Rhode & Kines, 1968, see Table 1, linear coefficients). However, when stroke volume in emus is expressed per gram of heart mass, the stroke volume to heart mass ratio (0.18 ml g^{-1}) is slightly lower than that reported for mammals (0.21 ml g^{-1}) (Holt *et al.* 1968, see Table 1, linear coefficients). Also it is similar to the stroke volume-heart mass ratio in pigeons (0.19 ml g^{-1}) and ducks (0.20 ml g^{-1}) (Grubb, 1982a). As the rate of oxygen consumption increased, stroke volume also increased. In one study, pigeons showed about a 40% increase in stroke volume with exercise (treadmill) (Grubb, 1982a), but in another study, stroke volume showed little change in flying pigeons (Butler *et al.* 1977). Ducks did not show an increase in stroke volume with treadmill exercise (Bech & Nomoto, 1982; Grubb, 1982a). No clear trend emerges from the literature concerning variability of stroke volume with exercise in dogs. In dogs, some studies report a stroke volume increase with exercise while others indicate little or no change (Barger *et al.* 1956; Rushmer, 1959). While stroke volume does increase in emus during exercise, the increase in heart rate is more important than stroke volume in increasing cardiac output in these as well as other birds. In humans, stroke volume usually shows a 1.27- to 1.60-fold increase during strenuous exercise (Musshoff *et al.* 1959; McDonough & Danielson, 1974).

In conclusion, we have studied some cardiovascular variables in the large terrestrial ratite bird, the emu, over a range of \dot{V}_{O_2} that is considerably larger than reported for other birds during treadmill running. Emus, as well as other birds that have been studied, seem to have a larger cardiac output for a given \dot{V}_{O_2} than mammals. This larger cardiac output may be partially due to the birds' lower arterial oxygen content. Emus fit the apparent avian trend of larger weight specific cardiac stroke volume as compared to mammals, and this seems to be related to birds having larger hearts than mammals of similar size.

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