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HEART MITOCHONDRIAL PROPERTIES AND AEROBIC CAPACITY ARE SIMILARLY RELATED IN A MAMMAL AND A REPTILE

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Summary

The heart mitochondrial properties and the aerobic capacity ($\dot{V}_{O_2max}$) of the rat (Sprague-Dawley breed) and the Cuban iguana (*Cyclura nubila*) were used to evaluate the relationship between the oxidative capacity of the heart and the maximum oxygen delivery rate. Both species are active at body temperatures of 37–39 °C, have similar heart mitochondrial volumes [V_{mt}; 0.43±0.02 ml (S.E.M.) in the rat and 0.48±0.02 ml in the iguana] and differ less than twofold in $\dot{V}_{O_2max}$ (29.2±1.6 and 16.9±0.6 ml min^{-1}, respectively). We found that V_{mt} was closely correlated with $\dot{V}_{O_2max}$ in the rat (r^2=0.77, P<0.005) and the iguana (r^2=0.82; P<0.001). Furthermore, the inner mitochondrial membrane (cristae) area (S_{im}) per unit $\dot{V}_{O_2max}$ did not differ between the rat and the iguana (0.60±0.02 and 0.71±0.02 m^2 min ml^{-1} O_2, respectively). This correspondence of $S_{im}/\dot{V}_{O_2max}$ indicates that the rat and the iguana have the same cardiac oxidative capacity at the maximum oxygen delivery rate. These results suggest that, despite the differences between the cardiovascular systems of these species, the cardiac cost of delivering oxygen at the aerobic capacity is similar in this mammal and this reptile.

Key words: *Cyclura nubila*, Cuban iguana, endurance training, exercise, heart, cardiac work, mitochondria, myocardium, Sprague-Dawley rat, $\dot{V}_{O_2max}$.

Introduction

The cardiovascular systems of mammals and reptiles differ greatly in their capacity for oxygen delivery (Gleeson *et al.* 1980; Johansen and Burggren, 1980; Karas *et al.* 1987). Mammals achieve a tenfold higher oxygen delivery rate compared with similarly sized reptiles, partly as a result of a higher cardiac output and elevated hemoglobin content (Burggren, 1987; Gleeson *et al.* 1980; Karas *et al.* 1987). One cost of increasing oxygen delivery is an elevation in cardiac work (Gibbs and Chapman, 1979). The higher blood pressure of mammals is expected to increase the cardiac work per unit oxygen delivered relative to the situation in reptiles. Yet the opposite effect is expected from the higher hemoglobin content of mammalian blood, since a larger oxygen content reduces the cardiac output and cardiac work necessary to deliver a given volume of oxygen. Thus, the factors that increase oxygen delivery rate may not disproportionately elevate the work per oxygen molecule delivered in the mammalian *versus* the reptilian cardiovascular systems.

A comparison of the delivery costs for oxygen for the two groups is possible from the maximum oxygen consumption rate during exercise ($\dot{V}_{O_2max}$). Both mammals and reptiles reach their maximum delivery rate of oxygen by the heart under this condition, as shown by the plateau in values for both cardiac output and heart rate at speeds approaching those that elicit $\dot{V}_{O_2max}$ (Gleeson *et al.* 1980; Karas *et al.* 1987). Evidence that this oxygen delivery limit coincides with the oxidative limit of the heart comes from the similar scaling of heart mitochondrial properties and $\dot{V}_{O_2max}$ with body size in mammals and reptiles (Else and Hulbert, 1985). A quantitative relationship exists in mammals between the area of the inner membranes of mitochondria and the activity of the respiratory chain enzymes. These enzymes are involved in generating the membrane potential that drives phosphorylation and in consuming oxygen at the terminus of electron transport (Schwerzmann *et al.* 1986, 1989). The activity of the terminal enzyme in the respiratory chain, cytochrome oxidase, has been found to differ twofold between reptilian and mammalian mitochondria (Hulbert and Else, 1989), which is close to the 1.6-fold difference in inner membrane density of these mitochondria (Conley *et al.* 1989; Hoppeler *et al.* 1984). The similarity of the ratios of inner membrane area and oxidative enzyme activity in mammals and reptiles indicates that the total area of these membranes is

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proportional to the maximum rate of oxygen consumption of the mitochondria in both groups (Schwerzmann *et al.* 1989). Therefore, the inner membrane area provides a measure of the oxidative capacity of the heart, while $\dot{V}_{O_2max}$ represents the maximum oxygen delivery rate to the tissues.

The purpose of this study was to deduce the oxidative cost of delivering oxygen in a mammal and a reptile, using heart oxidative capacity as a measure of the maximum rate of cardiac oxygen consumption and $\dot{V}_{O_2max}$ as a measure of the maximum rate of oxygen delivery. We used both intraspecific (individual variation) and interspecific comparisons to evaluate the relationship between these properties in the laboratory rat (Sprague-Dawley breed) and the Cuban iguana (*Cyclura nubila*). Both species exercise at a similar body temperature (37–39 °C) and were part of an endurance-training experiment (Conley *et al.* 1985, 1989; Kayar *et al.* 1986). First, we investigated how individual variation in the mitochondrial volume of the heart (the oxidative limit) corresponded with the range of $\dot{V}_{O_2max}$ (the oxygen delivery limit) in each species. Second, we made an interspecific comparison of heart mitochondrial properties *versus* $\dot{V}_{O_2max}$ to evaluate the cardiac oxidative capacity per unit maximum oxygen delivery rate in these two species.

Materials and methods

Animals and training procedures

Separate endurance-training experiments were performed on 15, 7-week-old Sprague-Dawley rats (mean body mass 0.35 kg, range 0.32–0.38 kg) and nine female Cuban iguanas (*Cyclura nubila nubila*, mean body mass 1.18 kg, range 0.98–1.30 kg). Rats were assigned, five to a group, to either 6 weeks of endurance training (trained), weekly measurement of $\dot{V}_{O_2max}$ (weekly run) or no exercise (control), as previously described (Conley *et al.* 1985). The heart masses and mitochondrial distribution within these hearts have been reported previously (Kayar *et al.* 1986). Data are reported only for the animals with matched tissue samples (N=9).

The iguanas were collected from a wild population under a permit issued by the Department of Natural Resources of the Commonwealth of Puerto Rico (Christian *et al.* 1986). Six individuals were collected from the field at the beginning of the experiments; three individuals were endurance-trained (trained group) and the remaining iguanas were cage-confined (control group) for a period of 8 weeks. A third group of three individuals was taken from the field (wild group) at the end of the 8 week treatment period to control for the effects of confinement on the animals caged for the duration of the experiment. Food and water were freely available to all animals. Mean values for the mitochondrial properties and $\dot{V}_{O_2max}$ of the iguanas in this study have been reported previously (Conley *et al.* 1989).

Experimental procedures

Respiratory gases were collected using a plastic mask which covered the head (Conley *et al.* 1985, 1989). These gases were drawn through an air- or mass-flow meter at a rate of 3–4 l min^{-1} (STP), pushed through a flask to dampen flow fluctuations, and pumped through H_2O (Drierite) and CO_2 (Ascarite) absorbers to an O_2 analyzer (Servomex model 570). For the iguanas, a separate line was split from the main line and led into an infrared CO_2 analyzer. Complete collection of the respired gases by the mask was confirmed by reducing the air flow rate by 25 % without affecting $\dot{V}_{O_2}$. Oxygen flow rate was calibrated before and after each experiment by bleeding known flow rates of dry nitrogen into the mask to dilute the ambient air (Fedak *et al.* 1981). Carbon dioxide flow rate was directly calibrated with known flow rates of dry CO_2.

$\dot{V}_{O_2max}$ *determinations*

Maximal oxygen consumption rate during exercise was determined from the animals at the end of the training period. The rats were run on a variable-speed and inclination ladder mill, whereas the iguanas were exercised on a motorized treadmill at a body temperature between 37 and 39 °C (the normal range found in free-ranging iguanas; Christian *et al.* 1986). Body temperature was measured before and after the exercise period by inserting a thermocouple into the cloaca (iguana) or rectum (rat). Prodding of the hindquarters ensured that the animals kept pace. Two criteria were used to establish the maximum value of $\dot{V}_{O_2}$: a constant oxygen consumption rate with increasing speed, and lactate accumulation rate. In the rat, an elevation in blood lactate concentration of 1 mmol l^{-1} min^{-1} confirmed that the constant $\dot{V}_{O_2}$ was maximal. A pilot study in the iguana showed that a net lactate accumulation rate occurred at a respiratory exchange ratio (RE: $\dot{V}_{CO_2}/\dot{V}_{O_2}$) greater than unity, as found earlier by Gleeson and Bennett (1982). We used RE as a non-invasive means of verifying that the plateau in $\dot{V}_{O_2}$ reflected a maximum value.

Training

Rats were endurance-trained by running for 25 min a day, 5 days a week at an intensity that elicited 85 % of the $\dot{V}_{O_2max}$ measured the previous week. The weekly run group was exercised only to measure $\dot{V}_{O_2max}$ (less than 5 min a week). Three rats were taken from each group at the end of the experiment for sampling of ventricular tissue. Endurance training in the iguana consisted of walking on a motorized treadmill for 15 min a day at 0.5 km h^{-1}, 5 days a week. The ventricular tissue of all nine lizards was taken for analysis at the end of the experiment.

Tissue sampling, fixation and analysis

Anesthesia prior to dissection consisted of premedication with diazepam (0.5 ml kg^{-1} body mass) followed by a pentobarbital injection (65 mg kg^{-1} body mass) in the rats and by injection with ketamine hydrochloride (5 mg kg^{-1} body mass) for the iguanas. The hearts were dissected free, blotted, weighed and the atria removed. The ventricles were weighed and a transmural sample was cut from the tip of the left ventricle for the rats and from the upper ventricular wall

for the iguanas. A single location was sampled for both species because extensive sampling had previously revealed a uniform mitochondrial composition (Anversa *et al.* 1985; Conley *et al.* 1989). All samples were processed using standard techniques (Hoppeler *et al.* 1981).

Morphometric measurements

Ultrathin sections (50–70 nm) were cut transverse or slightly oblique to the fiber axis, except where no fiber orientation was apparent, and counterstained. Four randomly selected blocks were examined at a final magnification of 24 000× to estimate the volume of mitochondria per volume of muscle fiber ($V_{v(mt,f)}$; ml mitochondria ml^{-1} muscle fiber). Forty micrographs per muscle were systematically sampled in consecutive frames of 200-square mesh grids from which points were counted using a B36 grid (144 test points; Hoppeler *et al.* 1981). Mitochondrial volume (V_{mt}; ml) of the heart was calculated from ventricular mass (M_v; g) and $V_{v(mt,f)}$ assuming that the volume density of fibers in whole muscle is unity:

$$V_{mt} = M_v V_{v(mt,f)}/\rho\,, \quad (1)$$

where ρ is muscle density (1.06 g ml^{-1}; Mendez and Keys, 1960).

Statistics

Means for the three groups were compared using a one-way analysis of variance (ANOVA). Significant differences among means were distinguished using Scheffe's *F*-test. Correlations between variables were evaluated using least-squares regression. The sample size necessary to distinguish between means for the measured variance was determined as follows (Schlesselman, 1973):

$$N = 2(Z_\alpha + Z_\beta)^2\sigma^2/\delta^2\,, \quad (2)$$

where N is the sample size, Z_α and Z_β are 1.96 and 1.282, respectively, for the 0.05 level of significance; σ^2 is the variance, and δ is the difference between means.

The fit provided by a single least-squares linear regression model for the results from both species was compared with that provided by separate regression models for the iguana and the rat using the methods of Hudson (1966):

$$F_{(df_1 - df_2)df_2} = [(RSS_1 - RSS_2)/(df_1 - df_2)]/(RSS_2/df_2)\,, \quad (3)$$

where F is the ratio of the variances, df_1 and df_2 are the degrees of freedom of the one- and two-model fits, respectively, and RSS_1 and RSS_2 are the residual sum-of-squares of the one- and two-model fits, respectively. All statistical analyses were undertaken using the STATVIEW 512+ program on a Macintosh.

Results

Myocardial structure

The heart of the rat and iguana differ substantially both at the gross anatomical and at the ultrastructural levels, as shown in Fig. 1. The left ventricular wall of the rat consists of a muscle layer made up primarily of a compact arrangement of muscle fibers and capillaries (Fig. 1A), while the iguana possesses a single ventricle consisting primarily of a spongy arrangement of fibers (Fig. 1B).

Training

Table 1 gives the physiological and structural properties of the three groups of rats engaged in the exercise program. Endurance training resulted in significant increases in $\dot{V}_{O_2max}$, body-mass-specific $\dot{V}_{O_2max}$ ($\dot{V}_{O_2max}/M_b$), heart mass (M_v) and heart mitochondrial volume (V_{mt}). No significant difference was found in $\dot{V}_{O_2max}/M_b$ for the weekly run group, although both $\dot{V}_{O_2max}$ and M_b were significantly higher than those of the control group. Table 2 shows that, in contrast to the rat results, the lizards from the wild and the trained groups showed no significant difference in any property relative to the controls.

Rat versus *iguana*

The two species differed significantly in both physiological and structural properties. There was a sixfold difference in $\dot{V}_{O_2max}/M_b$, but a less than twofold difference in $\dot{V}_{O_2max}$. The

Table 1. *Aerobic capacity and morphological properties of the rat heart*

		Treatment group		
Variable	Units	Control	Weekly run	Trained
$\dot{V}_{O_2max}$	ml min^{-1}	23.9 (0)	29.5 (0.5)*	34.1 (1.5)**
$\dot{V}_{O_2max}/M_b$	ml min^{-1} kg^{-1}	72.0 (2.3)	79.3 (2.1)	95.4 (5.2)**
M_b	g	332 (11)	372 (7)*	358 (5)
M_v	g	1.113 (0.031)	1.244 (0.037)	1.378 (0.021)*
$V_{v(mt,f)}$	%	35.4 (1.3)	38.2 (0.8)	36.8 (0.5)
V_{mt}	ml	0.37 (0.003)	0.45 (0.015)*	0.48 (0.005)**

Values are means (±S.E.M.), N=3 for all groups.

$\dot{V}_{O_2max}$, maximum rate of oxygen consumption; $\dot{V}_{O_2max}/M_b$, mass-specific maximum rate of oxygen consumption; M_b, body mass; M_v, ventricular mass; $V_{v(mt,f)}$, mitochondrial volume density; V_{mt}, mitochondrial volume.

Asterisks denote statistical differences from control: *P<0.05; **P<0.01.

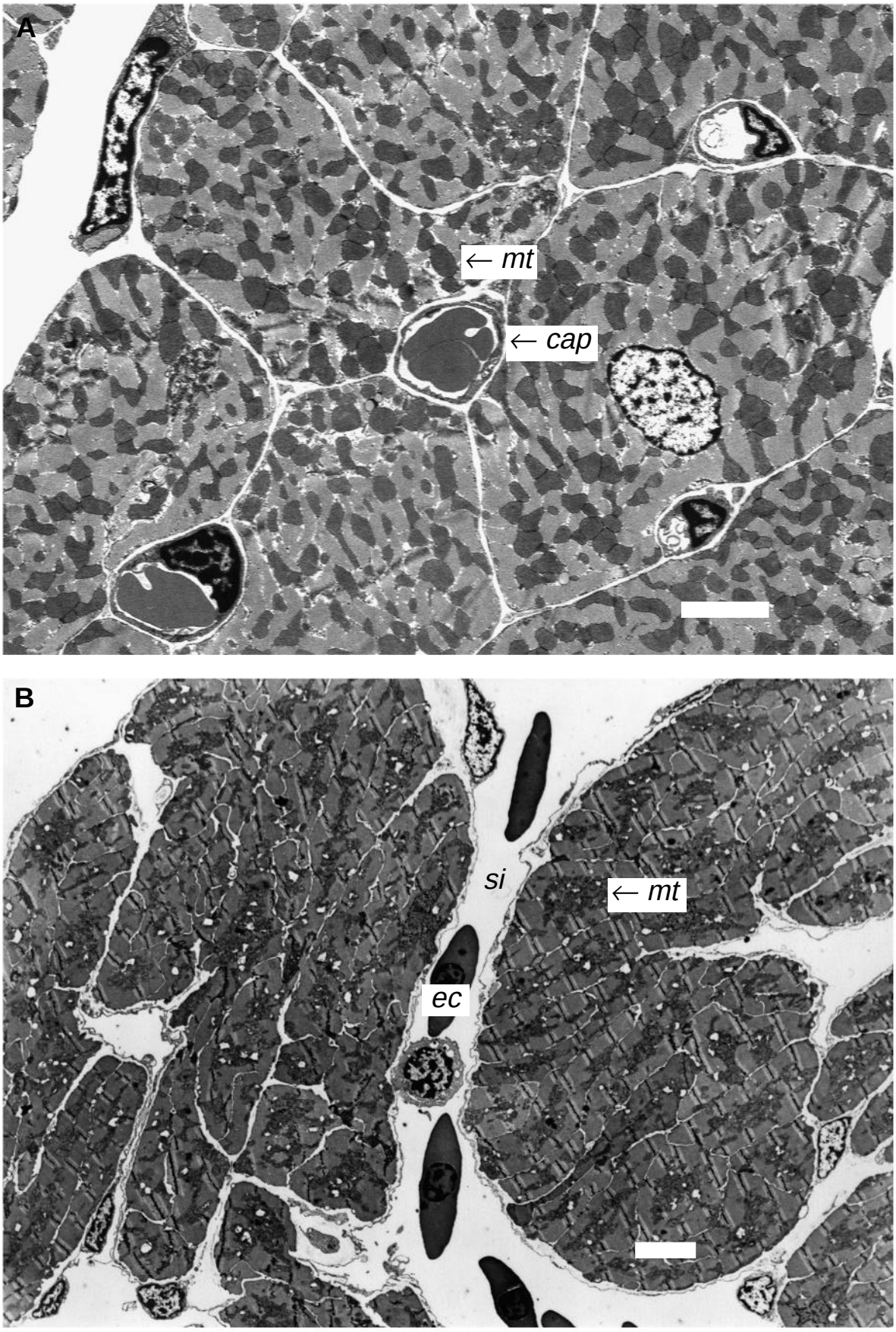

Fig. 1

Fig. 1. Electron micrographs of the ventricle of (A) the rat and (B) the iguana. The mitochondria (*mt*), erythrocytes (*ec*), a capillary (*cap*) and a blood sinus (*si*) are identified. Scale bars, 5 μm.

mean $V_{v(mt,f)}$ of the rat ventricle (36.8±0.63 %, S.E.M.) was nearly 1.5-fold greater than that for the iguana (24.0±0.69 %), while M_v was nearly twofold larger in the iguana (2.12±0.09 g) than in the rat (1.24±0.04 g). The lower $V_{v(mt,f)}$ in the iguana was balanced by the larger M_v, so that a similar mean ventricular V_{mt} (for all groups of each species) was found (0.43±0.02 ml in the rat *versus* 0.48±0.02 ml in the iguana). The smaller surface density of the inner membranes in the mitochondria of the iguana ($S_{v(im,mt)}$; 25.5±1.18 $m^2\,ml^{-1}$ mitochondria; Conley *et al.* 1989) compared with mammalian myocardial mitochondria (40 $m^2\,ml^{-1}$ mitochondria; Hoppeler *et al.* 1984) results in a smaller inner membrane area (S_{im};12.2±0.8 m^2) relative to the rat (17.2±0.7 m^2). This difference is in proportion to the disparity in $\dot{V}_{O_2max}$ between the two species and results in a value for $S_{im}/\dot{V}_{O_2max}$ that is not statistically different (P>0.15) between the iguana and the rat (0.71±0.018 *versus* 0.60±0.015 $m^2\,min\,ml^{-1}\,O_2$). The sample size of these two groups (N=18) exceeds the nine subjects necessary according to equation 2 to distinguish the groups, given the difference between the means (Δ0.09 $m^2\,min\,ml^{-1}\,O_2$) and the variance (0.003 $m^2\,min\,ml^{-1}\,O_2$; S.D.=0.054 $m^2\,min\,ml^{-1}\,O_2$) found in this study.

Cardiac structure versus *aerobic capacity*

The individual variation in the cardiac structural properties as a function of the aerobic capacity is shown in Figs 2 and 3. A significant correlation was found between M_v and $\dot{V}_{O_2max}$ in the rat (r^2=0.78, P<0.002), but not in the iguana ventricle (Fig. 2). In both species, the individual variation in ventricle V_{mt} was correlated with the variation in $\dot{V}_{O_2max}$ (r^2=0.77, P<0.005, rat; and r^2=0.82, P<0.001, iguana; Fig. 3).

The inner membrane area of the mitochondria was closely related to $\dot{V}_{O_2max}$ as shown by the regression in Fig. 4. We used the regression equations in Table 3 to investigate whether the slope of S_{im} *versus* $\dot{V}_{O_2max}$ differed between the rat and iguana. Because the confidence interval of the slope of the iguana line (0.18–1.7) overlaps the slope of the rat line (0.38), the two slopes are not statistically different. A second method for determining whether the slopes are different is to compare the fit of a single regression line with the fits of separate regression lines for each species using Hudson's method (1966). An $F_{5,13}$ value of 3.03 at the 0.05 level is evidence that two slopes

Table 2. *Aerobic capacity and morphological properties of the iguana heart*

		Treatment group		
Variable	Units	Control	Wild	Trained
$\dot{V}_{O_2max}$	$ml\,min^{-1}$	16.9 (0.9)	16.5 (1.5)	17.3 (1.0)
$\dot{V}_{O_2max}/M_b$	$ml\,min^{-1}\,kg^{-1}$	13.5 (0.8)	14.8 (0.4)	15.0 (0.2)
M_b	g	1254 (9)	1120 (97)	1152 (68)
M_v	g	2.33 (0.03)	1.87 (0.18)	2.16 (0.07)
$V_{v(mt,f)}$	%	22.8 (1.7)	24.5 (0.8)	24.5 (1.0)
V_{mt}	ml	0.50 (0.03)	0.43 (0.05)	0.50 (0.04)

Abbreviations are defined in Table 1.
Values are means (±S.E.M.), N=3 for all groups.

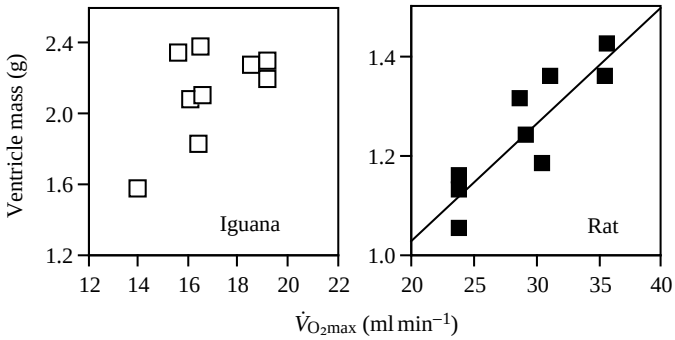

Fig. 2. Ventricular mass (M_v) as a function of maximum oxygen consumption rate ($\dot{V}_{O_2max}$) in the iguana and the rat.

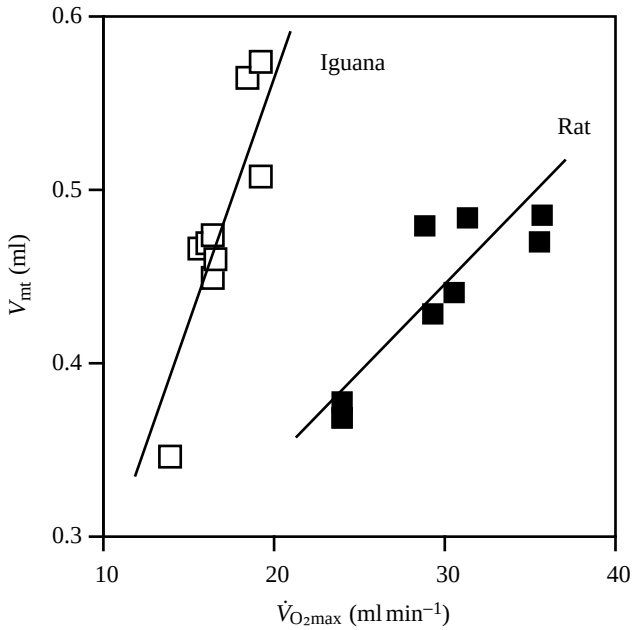

Fig. 3. Mitochondrial volume (V_{mt}) as a function of maximum oxygen consumption rate ($\dot{V}_{O_2max}$) in the iguana and the rat.

Table 3. *Regression relationships between ventricle inner membrane area (S_{im}) and maximum rate of oxygen consumption ($\dot{V}_{O_2max}$) in the rat and iguana*

	Slope	N	95 % confidence interval	Intercept	P
Iguana	0.96	9	0.18–1.7	–4.08	<0.03
Rat	0.38	9	0.20–0.56	6.16	<0.002
Iguana + rat	0.42	18	0.32–0.53	5.00	<0.0001

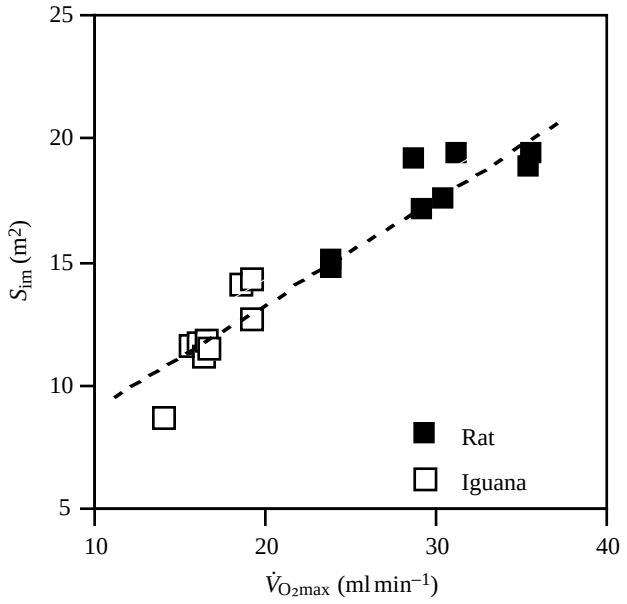

Fig. 4. Surface area of inner mitochondrial membranes (S_{im}) as a function of maximum oxygen consumption rate ($\dot{V}_{O_2max}$). The regression relationship between S_{im} and $\dot{V}_{O_2max}$ is shown by the dashed line.

account for the variance better than a single slope. The calculated F value of 0.75 for these data indicates that the variance of a single slope cannot be distinguished from two separate slopes. Thus, the slopes for each species do not represent the data better than does a single line incorporating the data from both species. We therefore cannot reject the null hypothesis that the rat and iguana data are represented by a single relationship between S_{im} and $\dot{V}_{O_2max}$.

Discussion

This study used the range of heart mitochondrial properties and maximum oxygen consumption rates among individuals following endurance training to examine how cardiac oxidative capacity relates to maximum oxygen delivery in a mammal and a reptile. We found that the individual variation of heart mitochondrial volume was closely related to $\dot{V}_{O_2max}$ in both species (Fig. 3) and that the inner mitochondrial membrane area (S_{im}) per unit $\dot{V}_{O_2max}$ did not differ between the rat and the iguana: 0.60 *versus* 0.71 $m^2\,min\,ml^{-1}\,O_2$. These values fall within the range of 0.34–0.71 $m^2\,min\,ml^{-1}\,O_2$ found in larger mammals running at their aerobic capacity (Karas *et al.* 1987). The overlapping range of $S_{im}/\dot{V}_{O_2max}$ for animals differing 1000-fold in $\dot{V}_{O_2max}$ indicates that cardiac oxidative capacity has a similar relationship to maximum oxygen delivery rate among these animals. This correspondence between the capacity for cardiac oxygen consumption and maximal oxygen delivery rate (i.e. $S_{im}/\dot{V}_{O_2max}$) suggests that the cost of delivering oxygen at the aerobic capacity is similar in this mammal and this reptile.

The correlation between S_{im} and $\dot{V}_{O_2max}$ for the two species is surprising, given the different operating conditions of the mammalian and reptilian circulatory systems (Gleeson *et al.* 1980; Karas *et al.* 1987). Two factors would tend to reduce the myocardial $\dot{V}_{O_2}$ of reptiles relative to that of mammals: the lower heart rates at the aerobic capacity (e.g. 100 and more than 200 beats min^{-1}, respectively; Gleeson *et al.* 1980; Karas *et al.* 1987) and reduced arterial pressures. However, because reptiles have a lower blood oxygen content than mammals (6–8 *versus* 13–23 ml O_2 100 ml^{-1} blood, respectively; Gleeson *et al.* 1980; Karas *et al.* 1987), a higher cardiac output and cardiac work are required for a given oxygen delivery. Thus, the lower pressures developed by the reptilian ventricle may be compensated by a higher cardiac output. Such a trade-off of developed pressure and cardiac output may account for the similar ventricular oxidative capacity per unit oxygen delivered at the aerobic capacity of these two species.

Estimates of cardiac mechanical work

We can evaluate whether a trade-off between developed pressure and cardiac output can account for the agreement of $S_{im}/\dot{V}_{O_2max}$ by estimating the oxidative requirements of the heart using cardiac mechanical work rate or power output ($\dot{W}$). Several factors determine this mechanical work rate (Farrell, 1991): cardiac output ($\dot{Q}$), mean systolic blood pressure (P_B) and the kinetic energy of accelerating the blood (E_k),

$$\dot{W} = \dot{Q}P_B + E_k . \quad (4)$$

Data in the literature are available for $\dot{Q}$ and P_B during exercise at the aerobic capacity for some species. However, few studies have quantified E_k during heavy exercise, which may lead to as much as a 25 % shortfall in the mechanical work estimate (see below). Cardiac output has been measured during exercise at $\dot{V}_{O_2max}$ in the rat (Gleeson *et al.* 1983) and we estimated the left ventricular mass as 80 % of total ventricular mass (Anversa *et al.* 1982). Values of $\dot{Q}$ at $\dot{V}_{O_2max}$ are available for only a few reptiles, such as the green iguana (*Iguana iguana;* Gleeson *et al.* 1980), which has similar M_b, $\dot{V}_{O_2max}$ and hemoglobin content to the Cuban iguana (Conley *et al.* 1989; Gleeson *et al.* 1980). Reported values of mean systolic blood pressure in mammals at the maximum aerobic capacity range from 18 to 23.3 kPa (mean 19.3 kPa) and are, on average, 45 % greater than the resting values (Karas *et al.* 1987). Blood pressures at the aerobic capacity have, to our knowledge, not been reported for reptiles, so we estimated the range of pressures using both the resting systolic pressure (6.4 kPa; Johansen and Burggren, 1980) and a value increased by the 45 % (6.4+2.9=9.3 kPa) increment observed at the aerobic capacity in mammals. Table 4 gives the mechanical work rates calculated from these values for the rat and iguana.

A trade-off between $\dot{Q}$ and P_B is evident between the two species in Table 4. The reported mass-specific $\dot{Q}$, calculated for the body mass of the species in this study, yields a 1.8-fold greater $\dot{Q}$ in the iguana than in the rat. In contrast, P_B is two- to threefold greater at the aerobic capacity in mammals than for our estimate for a reptile. As a result, the range of $\dot{W}/S_{im}$ for the iguana (3.2–4.7 mW m^{-2}) overlaps the value for the left

Table 4. *Estimated ventricular mechanical work rate for a reptile and a mammal exercising at* $\dot{V}_{O_2max}$

Animal	$\dot{Q}$ (ml s^{-1})	P_B (kPa)	$\dot{W}$ (mW)	S_{im} (m^2)	$\dot{W}/S_{im}$ (mW m^{-2})
Iguana	6.1[1]	6.4–9.3[3]	39.1–57.7	12[5]	3.2–4.7
Rat	3.4[2]	19.3[4]	65.6	14[5,*]	4.7*

Data are taken from: [1]Gleeson *et al.* (1980); [2]Gleeson *et al.* (1983); [3]Johansen and Burggren (1980); [4]Karas *et al.* (1987); [5]This study.

$\dot{Q}$, cardiac output; P_B, systolic blood pressure; $\dot{W}$, mechanical work rate; S_{im}, inner mitochondrial surface area; $\dot{W}/S_{im}$, mechanical work per unit inner mitochondrial surface area.

*Indicates data are for left ventricle only.

ventricle of the rat (4.7 mW m^{-2}). These values also overlap the range (4.4–6.7 mW m^{-2}) for data reported by Karas *et al.* (1987) for the left ventricle in mammals, where $\dot{W}$ was measured on the same hearts for which S_{im} was determined. Thus, the work rate estimates are consistent with the agreement in $S_{im}/\dot{V}_{O_2max}$ in the two species in this study and indicate that the ventricles of the rat and iguana are operating at similar $\dot{W}/S_{im}$ values.

A similar analysis is possible between the left and right ventricles of the mammalian heart. The uniformity of $V_{v(mt,f)}$ in the two ventricles of mammals (see Hoppeler *et al.* 1984; Anversa *et al.* 1982) means that oxidative capacity will be proportional to the mass of each ventricle. Since the same $\dot{Q}$ passes through both ventricles, then cardiac work will vary in proportion to the ratio of the pulmonary arterial (right ventricle) and systemic arterial (left ventricle) pressures. Holt *et al.* (1968) report, for mammals ranging in size from the rat to the horse, that the left ventricle constitutes 75 % of the ventricular mass and produces 83 % of the stroke work under resting conditions. At $\dot{V}_{O_2max}$ in humans, arterial pressure is found to be about three times higher than right ventricular pressure (20.5 *versus* 6.7 kPa; Rowell, 1993) in accordance with the threefold difference in ventricular masses (Olivetti *et al.* 1991). With $\dot{Q}$ and $V_{v(mt,f)}$ constant, this proportionality between the developed pressure and ventricular mass indicates that the right ventricle has the same $\dot{W}/S_{im}$ as found for the left ventricle in mammals. It then follows that the cardiac work needed to perfuse the pulmonary and systemic circulations by the left and right ventricles of mammals is accomplished by the single ventricle of reptiles.

Several lines of evidence support the conclusion that the cost of delivering oxygen at the aerobic capacity is similar in the rat and iguana. The correspondence of $S_{im}/\dot{V}_{O_2max}$ between these two species demonstrates that the oxidative capacity of the heart and the maximum rate of oxygen delivery are proportional. Consistent with this result are the mechanical estimates of cardiac work rate, which suggest that the hearts operate at similar work rates per unit inner mitochondrial membrane area. These results indicate that the differences in blood pressure, hemoglobin content and cardiac output between mammals and reptiles are not reflected in a disparity in the cost of delivering oxygen. Instead, the rat and the iguana heart appear to have a similar oxidative capacity per unit oxygen delivered to the tissues, despite the striking differences in the physiology and anatomy of the mammalian and reptilian cardiovascular systems.

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