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SHORT COMMUNICATION

Intraspecific scaling of arterial blood pressure in the Burmese python

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ABSTRACT

Interspecific allometric analyses indicate that mean arterial blood pressure (MAP) increases with body mass of snakes and mammals. In snakes, MAP increases in proportion to the increased distance between the heart and the head, when the heart–head vertical distance is expressed as $\rho g h$ (where ρ is the density of blood, $\boldsymbol{g}$ is acceleration due to gravity and h is the vertical distance above the heart), and the rise in MAP is associated with a larger heart to normalize wall stress in the ventricular wall. Based on measurements of MAP in Burmese pythons ranging from 0.9 to 3.7 m in length (0.20–27 kg), we demonstrate that although MAP increases with body mass, the rise in MAP is merely half of that predicted by heart–head distance. Scaling relationships within individual species, therefore, may not be accurately predicted by existing interspecific analyses.

KEY WORDS: Allometry, Scaling, Cardiovascular, Blood pressure, Snakes, Gravity

INTRODUCTION

The mean arterial blood pressure (MAP) generated by the heart of animals provides the driving force that ensures adequate perfusion of the various vascular beds to match metabolic requirements. MAP is made up of two principal components: the pressure required to overcome total systemic vascular resistance as well as the pressure required to overcome the vertical distance between the heart and upper extremities of the body, i.e. the gravitational (hydrostatic) pressure (Gauer and Thorn, 1965; White and Seymour, 2014). The gravitational pressure correlates directly to the vertical distance above the heart (h) and can be quantified as $\rho \boldsymbol{g} h$, where ρ equals the density of blood and $\boldsymbol{g}$ is acceleration due to gravity (Gauer and Thorn, 1965). Because the vertical distance between the heart and the upper extremities typically increases as animals increase in size, the greater gravitational forces predict that MAP increases with body size (Seymour, 1987; White and Seymour, 2014). Consistent with this view, the exceptionally high MAP in giraffes of approximately 250 mmHg, well above other similar-sized mammals, is typically viewed as an adaptation to overcome the large vertical distance between the heart and the head, and hence provide a normal perfusion pressure of the cerebral circulation (e.g. Patterson et al., 1965; Brøndum et al., 2009). In birds, MAP is higher than in mammals, but because MAP does not scale with body mass or the distance between the heart and the head, it has been suggested that factors other than gravity, such as metabolic rate, have major impacts on MAP (Seymour and Blaylock, 2000).

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The cardiovascular system of long-bodied animals, such as snakes, is particularly affected by gravity, and terrestrial and arboreal species are endowed with effective physiological mechanisms and structural adaptations that prevent pooling of blood in the lower body parts and maintain cardiac filling when body position is altered (Lillywhite, 1987; Lillywhite, 2005; Lillywhite and Donald, 1994; Lillywhite and Gallagher, 1985; Seymour and Arndt, 2004; Lillywhite et al., 2012). An interspecific comparison of 16 individuals belonging to nine different species of terrestrial snakes revealed a significant rise in MAP with body length, such that MAP increased proportionally to the distance between the heart and the head when expressed as the rise in gravitational pressure ($\rho \boldsymbol{g} h$) (Seymour, 1987).

Interspecific allometric analyses often provide fundamental relationships that transcend taxonomic differences (Savage et al., 2008); however, intraspecific and interspecific scaling relationships can differ significantly (Heusner, 1982; Thompson and Withers, 1997; Chappell and Ellis, 1987). To further understand how body size and head to heart distances affect MAP, we provide an intraspecific allometric analysis of heart rate (f_H), ventricular mass and MAP in the Burmese python *Python bivittatus* Kuhl 1820. As Seymour (Seymour, 1987), we measured resting undisturbed snakes in a horizontal position.

RESULTS AND DISCUSSION

The scaling relationship for ventricular mass in the python (Fig. 1, Table 1) was almost identical to the relationship reported for terrestrial snakes (Seymour, 1987). In contrast, the effects of body mass on MAP in the python (Fig. 1, Table 1) was considerably less than those measured in terrestrial snakes (Seymour, 1987). Regardless, in accordance with the previous allometric analysis (Seymour, 1987), MAP and ventricular mass of the Burmese pythons increased positively with body mass (Fig. 1, Table 1), while f_H decreased (Table 1). A regression through all data points predicts that f_H decreases from 22.7 to 9.5 min^{-1} when a Burmese python grows from 200 g to 30 kg. We did not measure stroke volume, but given that ventricular mass decreases from 1.8 to 1.2 g kg^{-1} over the same body mass interval, it seems very likely that cardiac output decreases similarly to reduction in f_H. This implies that most of the rise in MAP with increased body mass must be due to a rise in total systemic vascular resistance. Interestingly, the rise in MAP when expressed relative to the heart–head distance was also considerably lower than reported in the previous interspecific analysis for snakes (Seymour, 1987) (Fig. 2), where the relationship between MAP, measured in resting, horizontal snakes, and the heart–head distance,

List of symbols and abbreviations

f_H	heart rate
$\boldsymbol{g}$	acceleration due to gravity
h	vertical distance above the heart
MAP	mean arterial blood pressure
ρ	density of blood

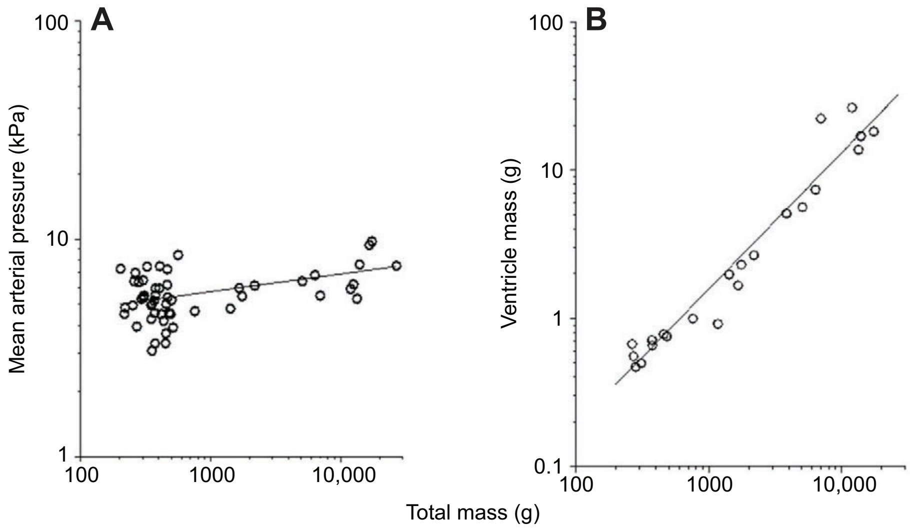

Fig. 1. Scaling of mean arterial blood pressure and mass of the cardiac ventricle in Burmese python (*Python bivittatus*). (A) Mean arterial blood pressure as a function of body mass for *P. bivittatus* (N=53). (B) Ventricle mass as a function of total body mass for *P. bivittatus* (N=22). Values are from fasted resting snakes at 30°C. Axes are logarithmic and the regression equation and statistics are presented in Table 1.

converted into a gravitational pressure (ρgh), had a slope of 1.18. If heart–head distance perfectly predicts MAP, this slope should be 1.0. In the 15 pythons where we have heart–head distances and MAP, the slope of the relationship was less than half of that reported for terrestrial snakes (Seymour, 1987) (slope=0.49 versus 1.18), and significantly less than 1.0 (P=0.0193). Thus, at least in Burmese pythons, MAP is not simply related to the heart–head distance. This result is not necessarily surprising. In a resting, horizontal snake, or any terrestrial vertebrate in a horizontal position, the heart and head are essentially at the same gravitational potential. Thus, the additional gravitational pressure component of MAP is eliminated and the hemodynamic challenges of perfusing the head are minimized.

A variety of factors may account for the different MAP scaling relationship found in *P. bivittatus* compared with existing interspecific analyses. Pythons, unlike any other group of snakes, have functional intraventricular separation of the pulmonary and systemic circulations, and hence sustain relatively high MAP, while keeping pressures in the pulmonary circulation low (Wang et al., 2003; Jensen et al., 2010). Consequently, MAP of pythons is already sufficiently high to overcome gravitational stress when the head is elevated. In addition, although the rise in MAP is well below that predicted by the longer heart–head distance, the reflexive neurogenic regulation of blood pressure may be sufficiently effective to overcome any vertical challenges whenever the head is raised above heart level (e.g. Lillywhite and Donald, 1994). Finally, the steeper interspecific scaling slope of MAP and heart–head distance reported by Seymour (Seymour, 1987) may have been biased by inclusion of many snake species adapted to an arboreal life style (scansorial).

Allometric analyses are generally insightful; however, interspecific and intraspecific analyses may depict dissimilar relationships. For example, the scaling of body mass and metabolism have yielded significantly different mass exponents when analysed intraspecifically versus interspecifically (e.g. Heusner, 1987). Therefore, it is not surprising that within the Burmese python, the allometric relationship of MAP and heart–head distance differs significantly from a phylogenetically diverse, interspecific relationship.

MATERIALS AND METHODS

Sixty-one Burmese pythons (*P. bivittatus*) with a body mass between 0.2 and 27 kg were purchased from a commercial supplier and kept at Aarhus University in vivaria equipped with a heating system that provided temperatures between 25 and 32°C. In addition, three of the largest individuals were studied at Universidade Estadual Paulista in Brazil. The snakes had free access to water and were fed once a week. Food was withheld at least 2 weeks prior to experimentation. The animals grew during captivity and appeared healthy.

Anesthesia was induced by inhalation of 5% isoflurane (Baxter, Denmark) to allow intubation for mechanical ventilation (1–2% isoflurane at 5–10 breaths min^{-1} and 50 ml kg^{-1}) using a Harvard apparatus mechanical ventilator. Snakes heavier than 2 kg were manually ventilated with an Ambu bag. Subsequently, a 5 cm ventrolateral incision was made anterior to the heart or posterior to the kidney, for the occlusive insertion of a polyethylene catheter (PE50 or PE90 containing heparinized saline, 50 IU ml^{-1}) in the vertebral artery or dorsal aorta, respectively. Snakes were allowed to recover for 1–2 days at 30°C.

To measure MAP, the arterial catheter was connected to a disposable pressure transducer (Model PX600; Baxter Edwards, Irvine, CA, USA) calibrated against a static water column and recorded with a Biopac MP100 data acquisition system (Biopac Systems, Inc., Goleta, CA, USA) at 100 Hz. f_H was derived from the pulsating pressure signal.

All measurements were conducted on fully recovered, fasting and undisturbed snakes kept at 30°C for a minimum of 12 h in climatic chambers that also served to reduce visual and auditory disturbance during measurements. Resting MAP and f_H were measured 1 h after connecting the catheters to alleviate the influence handling stress on MAP and f_H. All snakes studied in Aarhus were euthanized after measurements (200 mg kg^{-1} pentobarbital, i.p.), whereupon length was measured and hearts were harvested. The data reported in the present study were collected in

Table 1. Allometric equations for ventricular mass (M_v), mean arterial blood pressure (MAP), head–heart distance, total body length, heart rate (f_H) and body mass (M_b) in *Python bivittatus*

Y	*X*	Regression equation	*a*	*b*	r^2	*n*
M_v (g)	M_b (g)	$Y=aX^b$	0.00277	0.9187	0.958	22
MAP (kPa)	M_b (g)	$Y=aX^b$	3.248	0.0786	0.197	53
f_H (min^{-1})	M_b (g)	$Y=aX^b$	56.87	−0.1735	0.680	54
Head–heart distance (cm)	Total length (cm)	$Y=aX+b$	0.1905	2.814	0.971	23

All values were measured on fasting and undisturbed Burmese pythons at 30°C.

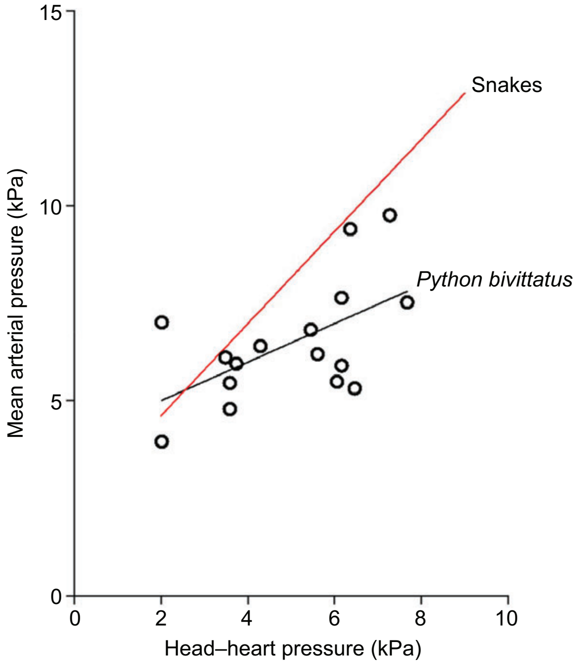

Fig. 2. Mean arterial blood pressure as a function of head–heart pressure (ρ*gh*) from 16 *P. bivittatus.* A straight line with the equation Y=0.4942X+4.017 is fitted to the data (black, r^2=0.3229). A regression from Seymour et al. (Seymour et al., 1987) is shown in red (Y=1.18X+2.26). Y, mean arterial pressure (kPa); X, heart to head distance converted to kPa. Blood was assumed to have a density of 1.05 g ml^{-1}.

connection with other experiments to determine regulation of the cardiovascular system, and the experiments were conducted in accordance with Danish Federal Regulations.

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Competing interests
The authors declare no competing financial interests.

Author contributions
All authors contributed to conception, design and execution of the study, and the interpretation of the findings. S.E., J.W.H. and T.W. wrote the manuscript, which was subsequently edited by C.S. and A.S.A.

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