The increase in metabolic rate during digestion and processing of meals is termed the specific dynamic action. In boid snakes, postmortem investigations have revealed postprandial physiologic adaptation of the gastrointestinal tract and heart; those studies revealed that the heart of constrictor snakes has a prodigious physiologic adaptation to their sit-and-wait foraging strategy and passes through a physiologic postprandial hypertrophy, which increases the specific dynamic action. Similar changes in organ size have been recorded for the pancreas, liver, kidneys, stomach, and small intestines, and Doppler ultrasonographic evaluation has revealed an increase in blood flow in the major vessels that supply the small intestines and liver.

Ultrasonographic evaluation of the heart is an important diagnostic tool in many species. In reptiles, echocardiographic information is comparably small and limited to physiologic and anatomic descriptions. The purpose of the study reported here was to noninvasively evaluate physiologic postprandial adaptations of the heart in snakes. Specific goals were to evaluate changes in heart size and the potential development of transient pericardial effusion. For this purpose, the hearts of juvenile snakes were evaluated at various feeding stages by use of echocardiography.

**Materials and Methods**

**Animals**—Six 11- to 12-month-old randomly selected female Paraguay anacondas (Eunectes notaeus) that weighed 126 to 216 g and were 62 to 79 cm in length were used in the study. The snakes had been bred and raised at the Zurich Zoo. Snakes were housed at the University of Zurich Vetsuisse Faculty Clinic for Zoo Animals, Exotic Pets and Wildlife, under standardized conditions (temperature, 26° to 28°C; relative humidity, 65%). The snakes were fed mice at monthly intervals. The study was approved by the Animal Care and Use Committee of the Canton Zurich.

**Procedures**—The examination and feeding programs were chosen on the basis of results of an earlier study. Briefly, food was withheld from snakes for 28 days, then each snake was fed a mouse (size of the

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mouse was 10% to 16% [mean, 13%] of the snake’s body mass). Snakes were evaluated immediately prior to feeding after the food-withholding period (day 0) and 3 and 10 days after feeding to test the hypothesis that cardiac mass increases after feeding.

Quantitative physical variables measured were body length (with each snake in a stretched position) and circumference at the level of the heart; measurements were obtained with a measuring tape. Body weight was determined with a digital scale.

Immediately after physical variables were measured, an echocardiographic evaluation was performed. The echocardiographic examinations included qualitative assessment and measurement of heart rate, and total and internal ventricular areas were determined in a single long-axis imaging plane. For echocardiographic examinations, snakes were manually restrained in dorsal recumbency on a heating pad at 28°C. All echocardiographic examinations were performed by the same investigator (TG) by use of coupling gel, a 14-MHz probe, and an ultrasound machine. Images were obtained at end diastole and stored for later measurements; those measurements were performed by investigators who were not aware of the identity of the snake or the day of the study on which the image was obtained. For each measurement, the arithmetic mean of 4 measurements was used for statistical analysis. Total and internal ventricular areas were measured by use of the manually aligned outer and inner silhouette of the myocardium (Figure 1); measurements were obtained with integrated software. The difference between the total and internal ventricular area (which represented the myocardial area) was calculated as a surrogate for myocardial mass.

Total ventricular volume was calculated by use of the single plane area-length method. This calculation has been validated only for the heart of mammals; however, for the study reported here, change in ventricular volume of the reptilian heart over time, rather than absolute values, was the focus. Therefore, calculations with a constant error were accepted.

Statistical analysis—Statistical analyses to compare data among the various time points were performed by use of a commercial program. Values of P < 0.05 were considered significant. The objective of the analyses was to determine whether there was a difference in analyzed variables among the 3 days of the study (0, 3, and 10) and whether there was a relationship between feeding, physiologic variables, and heart measurements. Results were reported as mean ± SD. Body length, body circumference, internal ventricular area, myocardial area, total ventricular volume, and heart rate were compared by use of an ANOVA. Data were analyzed for a normal distribution and comparable variance by use of the Kolmogorov-Smirnov and Hartley F max tests, respectively. When there was a significant result for the ANOVA, individual means were compared by use of a Bonferroni paired t test.

Results

Mean ± SD body length of the 6 snakes was 68.2 ± 6.0 cm on day 0, 68.3 ± 5.6 cm on day 3, and 69.0 ± 5.6 cm on day 10. Mean body circumference at the level of the heart was 66.0 ± 5.8 mm on day 0, 63.5 ± 5.7 mm on day 3, and 65.0 ± 7.1 mm on day 10. Mean body weight increased from 159.0 ± 35.3 g on day 0 to 167.7 ± 33.3 g on day 3 and then decreased to 156.7 ± 28.8 g on day 10. There were no significant differences in the physical variables.

During echocardiographic examination, image quality was rated as good in all snakes, and no artifacts created by air trapped under and around the snakes’ scutes were identified. In each snake at each time point, fluid was clearly delineated around the myocardium; however, this fluid represented blood vessels (specifically, the aorta and vena cava) as determined by use of color-flow and spectral Doppler ultrasonography. Pericardial effusion was not detected during any of the examinations.

Feeding had a significant effect on total ventricular volume, myocardial area, and heart rate. Data for total
Ventricular volume were normally distributed (P > 0.2) and had the same variance (P = 0.60). Mean ± SD total ventricular volume increased significantly (P = 0.021) from 4.63 ± 0.65 mL on day 0 to 5.54 ± 0.67 mL on day 10 (Figure 2). The changes from day 0 to day 3 (5.0 ± 0.98 mL) and from day 3 to day 10 did not differ significantly. Mean internal ventricular area was constant between day 0 (0.13 ± 0.02 cm²), day 3 (0.14 ± 0.03 cm²), and day 10 (0.13 ± 0.02 cm²).

Data for myocardial area was normally distributed (P > 0.20) and had the same variance (P = 0.77). Myocardial area varied significantly (P = 0.002) on the basis of feeding status. Mean ± SD myocardial area increased from 0.70 ± 0.08 cm² on day 0 to 0.75 ± 0.11 cm² on day 3 and to 0.81 ± 0.11 cm² on day 10. There was a significant (P = 0.008) increase in myocardial area from day 0 to day 10 (Figure 3).

Mean ± SD heart rate increased significantly (P = 0.036) from day 0 (45 ± 3 beats/min) to day 3 (52 ± 4 beats/min) and increased significantly (P = 0.044) from day 3 to day 10 (58 ± 10 beats/min; Figure 4). All measurements were independent of the relative mass of the ingested mouse.

**Discussion**

In the study reported here, postprandial changes in total ventricular volume, myocardial area, and heart rate were detected echocardiographically in juvenile Paraguay anacondas. The calculated total ventricular volume increased by 20% from day 0 to day 10. This finding is important for 2 reasons. First, this confirmed by use of noninvasive methods the previously reported physiologic cardiovascular adaptations associated with food withholding and feeding. Second, variability in echocardiographic variables associated with the nutritional status should be considered in future cardiac evaluations in anacondas and probably other infrequently fed snakes. The ultrasonographic settings used in the present study provided a good and constant image quality that allowed identification of cardiac anatomic structures and measurement of heart variables for cardiac evaluation, even in small snakes with short feeding intervals. The use of coupling gel instead of a water bath that was used in another study allowed high-quality ultrasonographic images without artifacts from trapping of air.

Postprandial changes in body mass and organ size are to be expected because of the weight of the ingested prey and also as a result of a concerted increase in metabolism and organ function associated with digestion. The increase in heart mass detected in postmortem examinations performed in snakes at various time intervals after feeding in other studies was detected ultrasonographically in the present study. Until the study reported here, ultrasonography had only been applied to the evaluation of organs of the digestive tract of snakes. In contrast to results of another study, a decrease or return to the preceding values by 10 days after feeding was not observed in the present study. In fact, all changes actually progressed from day 3 until day 10 (Figures 2–4), which indicated that the physiologic process of digestion and associated changes were slower in the snakes of the present study. Reasons for the difference in these results between the present study and other studies could have been the species of snakes, differences in prey items ingested, age, and environmental temperature.
Various snake species have been evaluated throughout the duration of the postprandial adaptation period. Duration of this period in boid adaptations ranges from 3.3 days in a boa constrictor (Boa constrictor) to 10 days in a ball python (Python regius). In the zoological systematically closer relative green anaconda (Eunectes murinus), changes in metabolic rate have been described as reversible after 8 days. Because no specific pattern associated with the various species could be found, the observed differences were most likely attributable to other factors.

Prey items affect the digestion process through their composition, type, temperature, and size. Meal composition and type of prey item have an impact on the peak of the metabolic response. Temperature of the prey item affects the specific dynamic action only when the meal temperature differs substantially from the body temperature of the snake. Although frozen prey items were carefully selected and warmed before they were fed to each snake in the present study, temperature of the mice may not have been optimal and may have slowed the metabolic process and adaptation. Meal size is an important factor for the time required for digestion in snakes, and the duration of the specific dynamic action response increases significantly with the relative prey mass in Python molurus, with a peak at 24 hours after ingestion of a relative prey mass comparable to that of the present study. Therefore, relative prey mass does not explain the constant increase of the heart variables for 10 days after ingestion in the present study.

Because the anacondas in the present study were 11 to 12 months old, age also could have been a factor. A study in green iguanas (Iguana iguana) revealed that young iguanas digest food more rapidly than do adults. Because the iguanas accomplish their shorter food transit by maintaining a higher body temperature, these differences are mainly attributable to housing temperature. The anacondas in the present study were housed at constant temperatures; thus, the factor of temperature selection could be ruled out. Nevertheless, the snakes in the present study were housed at a lower temperature (26° to 28°C) than were pythons in another study (30°C). Despite the fact that the housing temperature was within the recommended preferred optimal temperature zone, this temperature difference could explain the observed differences in time of physiologic adaptation of the heart as a result of the poikilothermic physiology of snakes. If reptiles are living in conditions with lower temperatures, their entire metabolism as well as the speed of physiologic adaptations are slowed. The lower temperature is most likely the major reason for the later-than-expected postprandial response. Long-term studies would be required to specify the basic principles.

The findings of a constant internal ventricular area and an increase in myocardial area can be described as concentric hypertrophy of the myocardium. In small animal practice, this could imply changes caused by pressure overload. Pressure overload leads to an increase in mechanical work, which can be accomplished by an increase in the rate of protein synthesis; an increase in the number of sarcomeres, which are laid down in parallel; an increase in mitochondria; and enlargement of myocytes. The detected change in heart size during food withholding in snakes could be attributable to a rapid new growth of ventricular tissue. Investigators in 1 study found a significant increase in the expression of mRNA for heavy-chain cardiac myosin during digestion. The newly synthesized protein is a result of increased transcription of the gene that encodes cardiac myosin heavy chains, and cardiac hypertrophy follows from de novo addition of contractile elements. The physiologic stimuli underlying this hypertrophy are unknown but are likely to include neural and humoral factors. Alternatively, changes in the myocardial interstitium (eg, swelling of myocardial cells associated with a higher work load) could explain changes in volume and mass during food withholding. Extrapolation of information for other species indicates that there are a number of conditions that cause concentric hypertrophy. The most important are outflow tract obstruction, systemic hypertension, hyperthyroidism, and hypertrophic cardiomyopathy. Furthermore, some conditions (eg, myocarditis or pseudohypertrophy caused by dehydration) may echocardiographically mimic hypertrophy. Theoretically, the myocardial area in the snakes of the present study could have been increased by artifact (ie, pseudohypertrophy caused by dehydration). However, for that situation, the internal ventricular area would have been decreased.

In addition to differences in organ size, differences in organ performance were also detected in the present study. Postprandial tachycardia has been described in humans, dogs, and snakes. A study in ball pythons, which were digesting a meal that constituted 25% of body weight, found that heart rate more than doubled within 24 hours after prey ingestion. Postprandial tachycardia is needed to increase cardiac output, which increases blood flow to the gastrointestinal organs. This increase in blood flow is needed to accomplish the postprandial increase in oxygen consumption, increase in metabolic rate during digestion, and increase in intestinal absorption. In the present study, heart rate was assessed 24 hours after prey ingestion, but a significant increase of the heart rate (29% increase) was detected between days 0 and 10, which again indicated that digestive processes were not completed in the snakes by 10 days after prey ingestion. Histamine can induce postprandial tachycardia through a direct effect on cardiac H₂-receptors in pythons. Additional studies will be required to prove whether this long-term increase detected in the present study was attributable to histamine.

Increased stroke volume (30% increase during exercise and 90% increase during digestion) has been reported in Burmese pythons, which further supports the concept of an increase in metabolic demand associated with digestion. In the present study, we did not attempt to evaluate systolic and diastolic variables. Pronounced translational motion of the heart precluded meaningful motion-mode measurements. Nevertheless, estimates of stroke volume could have been obtained by use of the single plane area-length method; unfortunately, heart measurements at systole were not obtained at the time of image acquisition. Therefore, in the pres-
ent study, an increase in cardiac output can only be postulated to have been a result of an increase in heart rate. Echocardiography in snakes has been performed only in larger species, such as adult Burmese pythons\(^1\) and carpet pythons (Morelia spilota variegata).\(^1\) In one of these reports,\(^2\) pericardial effusion was described but there was no further elaboration. Therefore, the present study was conducted to focus on the potential transient development of pericardial effusion. Clearly delineated echolucency around the heart as pathological effusion, which was suspicious for pericardial development of pericardial effusion. Clearly delineated study was conducted to focus on the potential transient development of pericardial effusion. Therefore, we propose that the described pericardial effusion was of pathological origin or an incidental misinterpretation of the heart near the caudal vena cava.\(^3\)

Echocardiographic data were obtained only in a single plane; therefore, calculated variables must be considered estimates rather than accurate calculations. For comparison over time, however, this method was considered to yield more accurate data than would be obtained by measurement in different planes with additional variability of data collection. Particularly in view of the complex system of incomplete septa in the heart of snakes, the selected long-axis view was considered to provide the most reproducible images.

Theoretically, there may have been a change only in cardiac shape associated with food withholding and feeding, without any change in volume or mass. However, whereas this may be theoretically true for internal ventricular volume, it seems unlikely that wall thickness, which was assessed by calculating myocardial area, would change asymmetrically (ie, thickened in one plane and thinned in another plane).

The present study revealed that echocardiographic examination of small snakes is possible, quantification of cardiac variables is possible, and physiologic postprandial changes in anacondas can be evaluated. Variability of echocardiographic variables (eg, heart rate, heart volume, and myocardial area) associated with the specific nutritional status of each snake must be considered in future standardized evaluations. Finally, care must be taken to ensure that unexplained findings in this poorly explored field are not overinterpreted. For example, inexperience may lead to interpretation of echolucency around the heart as pathological effusion, whereas knowledge of the specific anatomy combined with logic and good technical equipment will allow recognition of anatomically normal structures.

References


