SOME CIRCULATORY PROBLEMS IN REPTILES AND AMPHIBIANS

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To the comparative physiologist the physiological characteristics of reptiles are of great interest for a number of reasons. Birds and mammals are clearly reptilian in origin; hence a study of reptilian physiology may lead to a better understanding of function in homeotherms. Moreover, in the reptiles, one finds for the first time in nature a heart with two distinct ventricles and two distinct atria. This complete division of the heart has made possible the highly efficient circulation of the higher vertebrates.

The amphibians have always posed a problem. In many ways, they can be considered an evolutionary stage in the direct line from fish to man (Goodrich, 1930). However, careful examination of circulatory information suggests that the amphibians may be a branch leading to a blind alley and that the sequence fish, reptile, homeotherm more accurately outlines the facts (Foxon, 1955).

In discussions and study of the comparative physiology of circulation one is at a disadvantage when considering the reptiles and amphibians because of the fragmentary nature of our information. Data on cardiovascular physiology in these two poikilothermal groups are widely scattered in the literature and are characterized by significant gaps (Dittmer and Grebe, 1959; Prosser, 1950; Lepeschkin, 1951). This paper reports additional information on circulation in these important poikilotherms.

In the following discussion scientific names will be used where possible. In many references, however, only common names are used with no indication of the exact genus or species. Common names for animals are used in this paper when the precise scientific name cannot be found.

SIZE OF THE CIRCULATORY SYSTEM

The relative size of the circulatory system in amphibians and reptiles is summarized in table 1. Data for fish are included for comparison. From my own

TABLE 1

Average values for various characteristics of the circulatory system in reptiles, amphibians, and fish

Item	Reptiles	Amphibians	Fish
Heart weight (percent body weight, average)	0.216	0.220	0.086
Blood vol (ml/100 gm body wt)	3 to 8	4.6 to 8	1 to 6
Erythrocytes (million per mm³)	0.5 to 1.6	0.04 to 0.7	0.14 to 3.0
Oxygen capacity:			
Vol (percent packed cells)	29 to 83	25 to 33	23 to 35
Vol (percent blood)	6.6 to 15.3	2.5 to 23	4.2 to 19.8
Hemoglobin (per 100 ml blood)	5.7 to 11.3	6.0 to 10.2	8.7 to 37.1

experience with turtles of the Genus *Chelydra*, the average blood volume is about 3.3 percent of the total body weight using the dye dilution method.

THE HEART

Various reptilian species were used, unanesthetized, to obtain electrocardiograms. The general procedures have been described previously (Wilber, 1960). A direct-writing electrocardiograph was operated at the usual paper speed. The

general features of the electrocardiogram of reptiles resemble those of mammals. Table 2 summarizes ECG values for four species of reptiles studied.　Calculations

TABLE 2

Electrocardiographic values for four species of reptiles observed at 22°C

Genus	Rate (beats/min)	P-R (sec)	QRS (sec)	QR (mv)	T (sec)	T (mv)	Q-T (sec)
Alligator	40	0.40	.04	.12	.24	.05	0.60
Chelydra	35	0.56	.016	.25	.24	.20	1.12
Terrepene	39	0.40	.08	.50	.12	.11	0.88
Caretta	45	0.32	.16	.50	.20	.10	0.68

were made to illustrate time relationships.　The results of these calculations follow.

P–R Interval and Rate

The relationship of heart rate to P–R interval in various reptiles was calculated.　At a mean heart rate (based on all the species tested) of 48 ± 15 beats/min, the mean P–R interval was 0.33 ± 0.13 sec.　P–R interval was found to vary inversely with rate,

$$Y = 0.68 - 0.0072 \text{ x } (r = -0.885)$$

where Y is the P–R in seconds and x the heart rate in beats per minute.

In man, increase of the heart rate is normally accompanied by a decreased P–R interval.　In several species of animals, including the frog, it is reported that increased heart rates produced by warming the sinus or by changing the rate of artificial stimulation are accompanied by a lengthening of the P–R interval (Lepeschkin, 1951).

Q–T Interval and Cycle Length

The relationship of the Q–T interval to the total cycle length (R–R) has been studied by numerous investigators who were interested primarily in the human heart (Lepeschkin, 1951).　An evaluation of the relationship of the Q–T interval to cycle length using graphic methods of analysis led Robb and Turman (1947) to conclude that, "In laboratory animals the QT/cycle ratio seems more significant than mere QT duration."　In reptiles such analysis has not been made to the best of my knowledge.　Therefore, it was decided to compare the Q–T interval and cycle length (R–R) in a variety of reptiles having different heart rates.　The following genera were included (numbers in parentheses indicate number of individuals): *Caretta* (3), *Alligator* (6), *Elaphe* (2), *Chelydra* (6), *Terrepene* (6), *Pesudemys* (6), *Anolis* (5).　Thirty-four individuals were studied. The value of a constant, K· was calculated for each individual using the formula,

$$QT = K \sqrt{R-R}$$

It was found that the average value for K, based on all individuals tested was 0.78 ± 0.19 at an overall mean heart rate of 43 ± 16 beats/min.　K varies inversely with heart rate as follows,

$$K = 1.181 - 0.0091 \text{ x } (r = 0.77)$$

where x is the heart rate in beats per minute.　The relationship holds for reptilian heart rates from 20 to 90 beats/min.

If R–R is plotted against Q–T for all reptiles and heart rates observed, a linear relationship is apparent: $Y = 0.645$ x, where Y is Q–T in seconds and x is RR in seconds.　In other words, Q–T in the genera of reptiles studied makes up a little more than 0.6 of the total cycle duration.　The relationship holds for heart rates from 20 to 90 beats/min.　The mean value for Q–T based on all reptiles studied and for all heart rates was 0.9 sec; the R–R, 1.3 sec.

Rate and Temperature

As is true for cardiac muscle in general, the rate of beat of the reptilian heart increases with elevation of the temperature. In our experience the increase in rate varies directly with temperature.

Experiments were made on intact specimens of *Pseudemys* sp. exposed to various temperatures in an incubator. Heart rate was recorded as previously with a direct-writing electrocardiograph. The results of 5 experiments on each of 9 turtles show that heart rate is related to temperature as follows:

$$Y = 3.57 \; x \; -56 \; (r = 0.99)$$

where Y is the heart rate in beats per minute and x is the cloacal temperature in °C. The results show also that the temperature coefficient (Q_{10}) varies with temperature. By calculation from the raw data the Q_{10} for the heart in *Pseudemys* was found to be:

> Between 20° and 30°C, 3.3
> Between 25° and 35°C, 2.1
> Between 30° and 40°C, 1.7

In the past too much emphasis has been attached to the Q_{10} value for biological functions. Recent awareness of the fact that the temperature coefficient might be a coincidental value resulting from the summation of an unknown number of velocity constants and that it changes with temperature has resulted in a re-evaluation of the concept. For example, Heilbrunn (1952), in discussing the so-called van't Hoff rule, says: "This rule is not to be taken too seriously. However, the fact that biological Q_{10}'s are often between 2 and 3 may have significance."

If one understands that the Q_{10} value for biological processes has no rational basis, it is then safe and useful to use the value as a convenient means for comparing the action of temperature on a variety of biological functions.

In the isolated heart of the frog (Dittmer and Grebe, 1959), rate of beat varies directly with temperature according to the equation,

$$Y = 2.19 \; x$$

where Y is the rate in beats per minute and x is the temperature in °C of the fluid surrounding the heart. The heart in the intact frog follows the following relationship up to about 25°C:

$$Y = 4.8 + 1.1 \; x$$

Above 25°C the heart rate decreased until at 36°C it averages about 25 beats/min (Dittmer and Grebe, 1959).

The average response of the heart rate in fish to temperature, from 0° to 30°C follows the line,

$$Y = 6 + 1.25 \; x$$

It is clear that the slopes for increase in heart rate with temperature in intact fish and frog are nearly the same and that the rates at 0°C are almost identical. The isolated frog heart, on the other hand, has nearly twice the rate slope and at 0°C is virtually at a standstill. The Q_{10} values for various temperature ranges are summarized in table 3 for fish and frog. It is evident that the Q_{10}'s for frog

TABLE 3

Table showing the variation with temperature of
Q_{10} values for the beating frog heart

Heart	5 to 15°C	10 to 20°C	20 to 30°C
Isolated, frog	3.2	1.3	1.5
Intact, frog	2.1	1.7	1.1
Intact, fish	2.1	1.7	1.4

and fish hearts, as for reptilian, vary with temperature. As a general rule in the poikilotherms, the Q_{10} value decreases with increasing temperature.

Table 4 summarizes the relationships of heart rate to temperature in frog, fish and several reptiles.

TABLE 4

Values of a and b in prediction equations, $Y = a + bx$, relating heart rate (Y) to temperature, °C (x)

Animal	a	b
Frog, isol. heart	0	2.19
Frog, intact	4.8	1.10
Fish	6.0	1.25
Pseudemys	−56.0	3.50
Alligator	−1.3	1.67
Chelydra	−3.3	1.88

The values as given in table 4 for *a* and *b* in reptiles hold for temperatures up to about 35°C; above that temperature the hearts begin to show signs of disorganization.

These data support the view that the Q_{10} value is itself a function of temperature (Heintzen, 1958).

Origin of the Beat

In the heart of the frog or turtle the sinus venosus is the pacemaker; its intrinsic rate is higher than that of the atrium, ventricle, or bulbus arteriosus (Bayliss, 1960).

In the alligator, the sinus venosus is also the pacemaker of the heart (Wilber, 1960). The wave of negativity passes over the alligator heart as follows:

1. Sinus venosus
2. Right atrium
3. Left atrium
4. Base of ventricles
5. Apex of ventricles

Which ventricle is first excited is not known.

BLOOD PRESSURE

Mean ventricular blood pressures taken with the aid of a mercury manometer on several species of turtle gave an average value of 17.6 mm Hg, SD ± 5.9, SE ± 2.2. Table 5 gives individual values. These values are low compared with

TABLE 5

Average mean systolic blood pressures for various turtles

Temp (°C)	Mean pressure (mm Hg)	Remarks
22	20	*Terrepene*, pithed
22	20	*Terrepene*, pithed
22	27	*Chrysemys*, ventricle
22	16	*Chrysemys*, ventricle
22	14	*Chrysemys*, truncus
22	15	*Chrysemys*, truncus
24	11	*Chrysemys*, truncus
22	15	*Lepidochelys*, pulm. A.

some reported in the literature, where mean arterial pressures between 18 and 35 mm Hg are listed (Dittmer and Grebe, 1959). Temperature, season of the year, and physiological condition of the animal may all be involved in determining the average mean blood pressure. These variables have not been well controlled or accounted for in most publications to date.

CARDIAC RESPONSES TO DIVING

Alligators, subjected to a simulated dive, respond with a profound bradycardia which persists even during a struggle under water (Wilber, 1960a). The onset of bradycardia in the intact alligator occurs about 4 to 5 min after submersion. The heart rate drops to as low as 1 beat/min. Whether low tissue oxygen content or elevated carbon dioxide content is responsible for the decreased heart rate is not clear.

An experimental approach was made to the problem in my laboratory. Alligators were subjected to simulated dives by immersion of the head in water, carbon dioxide, or nitrogen. The exposure chamber consisted of a glass cylinder fitted over the head of the animal and sealed around the neck with rubber dam. Glass tubes were fitted through a rubber stopper which sealed the open end of the cylinder. The glass tubes served as inlet and outlet passages for gases or water.

If water were run into the cylinder to cover completely the alligator's head, the heart rate fell as expected. Examination of the electrocardiogram under these conditions revealed that time intervals for P, P-R, and QRS remained virtually unchanged from control values; Q-T interval was lengthened as much as two-fold. Occasional inversions of the T wave occurred during the dives. When the water was drained from the cylinder and air readmitted the heart rate regained control level in a few seconds.

After a suitable rest period, if 100 percent carbon dioxide were run into the cylinder so that the alligator was forced to breathe an atmosphere of the pure gas, the heart rate again decreased. The animals continued to breathe while in the CO_2 atmosphere. Return of the heart rate to control level was much slower after removal of the alligator from the CO_2 than from water submersion. A CO_2 concentration of 50 to 100 percent in air gives the above response; concentrations below 50 percent fail to induce a clear-cut and sustained bradycardia.

The above experimental procedure was repeated using 100 percent nitrogen in the cylinder. An extremely erratic heart rate resulted. Breathing continued.

TABLE 6

Cardiac response of alligator to diving

Item	Water	CO_2	N_2
Mean heart rate during exposure	23	24	24
Minimum heart rate during exposure	8	2	12
Onset of bradycardia, min	2	2	2
Recovery time, min	0.5	20 to 30	5 to 6
Control heart rate		35 to 40	

A decrease in amplitude of all components of the electrocardiogram was evident as were inversions of the T wave. After 18 min of nitrogen breathing the alligator showed only mild narcosis and the heart rate continued to fluctuate from near control levels to a few beats per minute. Recovery of control heart rate after return to air was delayed for 6 min. The mean heart rate during the nitrogen breathing was 24 beats/min; the control was 32 beats/min. A summary in tabular form of the alligator's cardiac response to submersion in water, carbon dioxide, or nitrogen is shown in table 6.

Several experiments were made to ascertain whether the bradycardia associated with diving could be erased by atropine. The results were unsatisfactory. In a few trials with alligators given atropine sulfate, 20 mg/kg intraperitoneally, there was a suggestion that the slowing of the heart was less marked during diving than in control animals. Two animals given 50 mg/kg atropine sulfate showed no bradycardia during diving; both died shortly after removal from the water. Intravascular injections of atropine, in doses as low as 2 mg/kg, caused a slowing of the heart even before diving. The result probably stemmed from the direct

action of the drug on the myocardium. Recent studies on the physiological responses of the alligator to diving have confirmed and extended this work in a series of critically designed and executed experiments (Andersen, 1961).

Five specimens of the bullfrog, *Rana catesbiana*, were forced to dive while connected through appropriate leads to a direct-writing electrocardiograph. Bradycardia occurred during diving; but it was not so profound as in the alligator. For example, in one experiment carried out at 22°C on the bullfrog with a control heart rate of 56 beats/min, the heart rate dropped to 47 beats/min within 15 sec after immersion. The rate then fluctuated from about control level (55 beats/min) to below control until a minimum rate of 43 beats/min was reached 10 min after immersion. When the frog was resurfaced, the heart rate rose to 65 beats/min within 15 sec. It gradually slowed and reached control level 5 min after surfacing. This overshoot of the heart rate is a regular response in the bull frog after diving. It has never been observed in the reptiles studied in this laboratory.

In order to get further information on the responses of the frog, *Rana catesbiana*, to diving, 5 experiments at each of 2 temperatures were made. Heart rate was recorded before, during, and after experimental dives. Table 7 summarizes the results.

TABLE 7

Rate response of heart in bullfrog, Rana catesbiana, *to simulated diving in water at 2 different temperatures.*

Averages of 5 experiments.

Item	30°C	22°C
Mean heart rate during dive	63	54
Minumum heart rate during dive	31	48
Control heart rate	97	63
Decrease to mean, percent of control	65	86
Decrease to minimum, percent of control	32	76

As one would expect, the control heart rate and the mean heart rate during diving were greater in 30°C than in 22°C water. However, the minimum heart rate reached was lower in warm than in cold water. In 30°C water the heart rate during diving was depressed nearly 3 times as much, on a percentage basis, as it is in 22°C water. The reason is not clear.

CONCLUSIONS

Conclusions which are derived from a discussion of cardiac physiology in amphibians and reptiles are essentially recognitions of areas of ignorance.

Precise values, based on suitable numbers of individuals and of species, for blood pressure (mean, systolic, diastolic, pulse) in reptiles and amphibians are wanting. Published values for blood volumes in these 2 classes of poikilotherms are few and unsatisfactory. Anatomical and basic physiological characteristics of the vascular system in reptiles are complicated in the turtles by the large shell mass.

A worth-while study of the heart in a number of species of reptiles and amphibians should include a critical evaluation of the relationship of various parts of the cardiac chambers as related to mechanical and electrical activities in the myocardium, and a more thorough comparison of the responses of the isolated and intact hearts to various environmental variables.

Finally, one wonders whether there is any phenomenon akin to shock in these animals. From the evolutionary point of view, it seems fitting that biological precursors of the shock syndrome should be found, especially in reptiles. The discovery of such precursors might be of unique value in understanding the mechanism of terminal shock in man and other mammals.

REFERENCES

Andersen, H. T.   1961.   Physiological adjustments to prolonged diving in the American Alligator, *Alligator Mississippiensis.*   Acta physiol. scand. 53: 23–45.

Bayliss, L. E.   1960.   Principles of general physiology.   Vol. II.   Longmans, New York. 848 p.

Dittmer, Dorothy S., and **R. M. Grebe** [ed.].   1959.   Handbook of circulation.   WADC Tech. Rept. 59–593.   Wright-Patterson Air Force Base. 393 p.

Foxon, G. E. H.   1955.   Problems of the double circulation in vertebrates.   Biol. Rev. 30: 196–228.

Goodrich, E. S.   1930.   Studies on the structure and development of vertebrates.   Macmillan, N. Y. 837 p.

Heilbrunn, L. V.   1952.   An outline of general physiology.   3rd. ed.   Saunders, Philadelphia. 818 p.

Heintzen, P.   1958.   Die mathematische Behandlung der Temperaturabhängigkeit biologischer Prozesse.   Pflügers Arch. ges. Physiol. 266: 207.

Lepeschkin, E.   1951.   Modern electrocardiography.   Williams and Wilkins, Baltimore. 905 p.

Prosser, C. L. [ed.].   1950.   Comparative animal physiology.   Saunders, Philadelphia. 888 p.

Robb, Jane S., and **W. G. Turman.**   1947.   Further considerations of the QT interval.   Am. J. Med. Sci. 214: 180–192.

Wilber, C. G.   1960.   Effect of temperature on the heart in the alligator.   Am. J. Physiol. 198: 861–863.

———.   1960a.   Cardiac responses of *Alligator Mississippiensis* to diving.   Comp. Biochem. Physiol. 1: 164–166.