

THE TOTAL ENERGY EXCHANGES OF INTACT COLD-BLOODED ANIMALS AT REST. BY A. V. HILL,
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IN a discussion of the metabolism of an animal one factor is of primary importance, viz. the amount of chemical energy degraded. The total food-supply is, of course, a measure of this quantity, provided always that no food is retained in the tissues: so also are the O₂-intake and CO₂-output, provided that the type¹ of substances being oxidised is known. These conditions are however not easy to satisfy: a direct calorimetrical experiment, in which the mechanical work² done is summed and estimated together with the heat produced by the tissues, is therefore far preferable. In the case of the cold-blooded animals, the calorimetrical is really the only way: the animals will not feed properly in confinement, and they seem to have the power of retaining CO₂ in their tissues for long periods. An estimation of the total heat-production of these creatures will afford, therefore, the only valid inferences one can draw, as to the course and intensity of the chemical reactions in their tissues. Such experiments have, of course, been done before, both upon developing eggs³, micro-organisms⁴, and plants⁵. The methods employed, though of interest, were however unsuitable to the case of experiments of long duration upon cold-blooded animals. Such experiments I have carried out, therefore, with the differential micro-calorimeter described recently in this *Journal*⁶. The animals employed have been frogs, newts, snakes, and worms, living under various conditions.

¹ *I.e.* whether protein, fat, or carbohydrate.

² Turned into heat in the calorimeter.

³ Bohr and Hasselbalch. *Skand. Arch. f. Physiol.* xiv. p. 398. 1903.

⁴ Rubner. *Hygienische Rundschau*, xvii. 1903. *Arch. f. Hygiene*, xlviii. p. 260. 1903. *Ibid.* xlix. p. 355. 1904; lvii. p. 229. 1906. P. Nawiascky. *Ibid.* lxxvi. p. 209. 1908.

⁵ Rodewald. *Jhrb. d. Bot.* xviii. p. 276. 1887; xix. p. 221. 1888.

⁶ A. V. Hill. *This Journal*, xliii. p. 261. 1911.

i. *The uniformity of the heat-production, as measured by the micro-calorimeter.*

In a previous paper¹ one experiment has been given upon the heat-production of normal living frogs. Reference to this will show that, after an hour or two, the evolution of heat became linear with the time. This is of some importance for the validity of the method, so that other experiments in the same connection are given here.

Exp. i (a) and (b). Two experiments were done with the same control flask.

(a) Seven frogs=108 c.c.+150 c.c. water, in flask No. 3. 100 s.d.= -387° C.

(b) Six frogs=97 c.c.+163 c.c. water in flask No. 10. 100 s.d.= -386° C.

340 c.c. water at 20° C. in control flask No. 6. For each flask $k=0.53$.

Time in hours	0	1.0	2.45	3.9	4.3	4.5	6.1	6.95	9.65
Reading No. 3	-76	-31	+20	+90	102	117	160	180	288
Reading No. 10	-173	-129	-69	-13	0	+8	73	100	204

The curves corrected for heat-loss are given in Fig. 1. It is seen

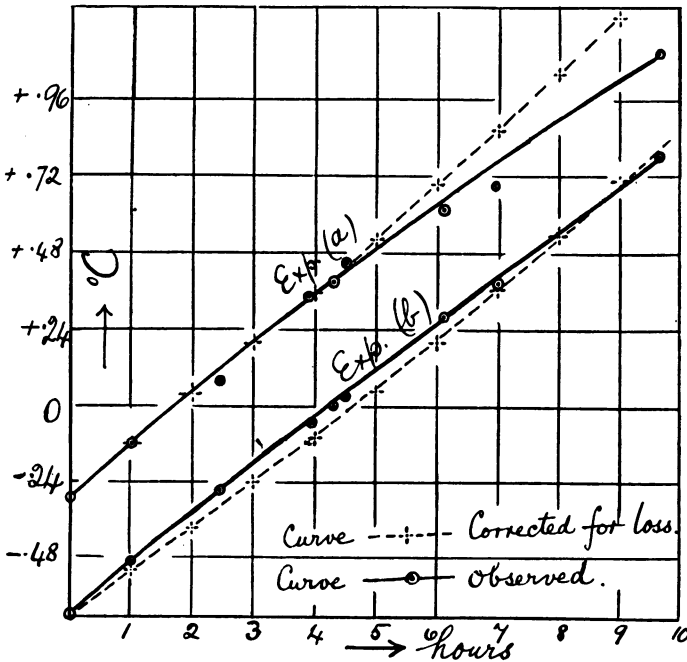


Fig. 1. Heat production of frogs: to show linear nature of heat-production.

¹ *Loc. cit.* p. 279, Fig. 7.

that the heat-production is closely linear. In Exp. i (a) the value of the heat-production is 45.5 s.d. per hour, *i.e.*

$$\frac{.455 \times .387 \times 278}{108}$$

or 0.453 calorie¹ per c.c. of frog per hour.

In Exp. i (b), the value is $\frac{.425 \times .386 \times 280}{97} = 0.474$ cal. per c.c. of frog per hour.

The concordance observed between the results of these two simultaneous experiments, upon the same batch of frogs, is striking. The temperature of the frogs was between 20 and 21° C. during the experiment.

Exp. ii. Frogs kept in laboratory four weeks (Oct. Nov.).

155 c.c. frogs + 205 c.c. water in flask No. 5. 312 c.c. water in flask No. 1. 100 s.d. = 328° C. $k = .0344$.

An observation was not made till three hours after the animals were placed in the flask.

In the third line below are given the readings as corrected for heat-loss: in the fourth the values as calculated on the assumption that the heat-production is linear, and that the first and last values are correct.

Mean temperature during experiment 13.4° C.

Time in hours	3	5	6.4	8.8
Reading observed	+25	81	123	187
Reading corrected	25	84.6	131.6	215.6
Reading calculated	25	88.0	132.0	215.6

The heat-production is here also perfectly linear, as is seen from the concordance between "corrected" and "calculated" values. The actual evolution of heat amounted to .168 cal. per c.c. of frog per hour.

Exp. iii. Grass-snake = 84 c.c. + 216 water in flask No. 10, at 23.7° C.

330 c.c. water in flask No. 9. $k = .0476$; 100 s.d. = 369° C.

"Corrected" and "calculated" mean the same as in Exp. ii.

Time in hours ...	0	1.4	4.1	6.0	7.9
Reading ...	-262	-187	-65	+14	+63
Corrected reading	-262	-205	-94	-22	+36
Calculated reading	-262	-205	-100	-26	+47

It will be seen again that the concordance between calculated and corrected values is very good. The heat-production is strikingly linear and has the value 0.55 cal. per c.c. snake per hour.

This phenomenon of the linear production of heat has been seen many times: the above are only three examples out of perhaps 100.

¹ Throughout this paper calorie is used for gram-calorie.

We might of course expect that under certain conditions the rate of evolution of heat should be uniform : such conditions are :

(i) That the animals remain at rest during the experiment. For it is improbable that they should move about regularly the whole time.

(ii) That the temperature remains constant.

(iii) That confinement in the calorimeter does not injure the animals during the period of the experiment: partial asphyxiation for example might very seriously affect the heat-production.

The observed linearity therefore renders highly probable, though of course it does not prove, that each of these conditions is satisfied. With respect to the first, it was noticeable in a few experiments upon frogs and newts at low temperatures, that the heat-production was absolutely irregular. For periods of half an hour it might be low, then during the next half hour it might reach a value three or four times the previous one. It is of course impossible to look into the flasks during an experiment. The frogs were however much more excitable at low temperatures (such as 14° C.) than at high (such as 24° C.), and seeing that the irregularity occurred only at low temperatures it seems to me practically certain that, except in these obviously irregular cases, the animals remain completely at rest during the experiment. When they are first put into the flasks they jump about for some time before they finally settle down quietly. There is also, in general, an exceptionally high heat-production during the first hour or two. It seems therefore certain that, in the cases in which the heat-production is linear, the animals are remaining at rest the whole time.

With regard to the constancy of the temperature in the calorimeter, the Dewar flasks are such good insulators of heat that one may usually feel certain that the temperature is constant within a degree; the heat produced by the animals themselves is not sufficiently large to disturb this, except in the case of experiments at high temperatures: in these however there is a *loss* of heat by conduction, which tends to balance the heat given out by the animals.

With regard to the third condition, I have often used frogs day after day for these experiments: in fact 12 frogs have been kept in the laboratory for four weeks, during which time they have spent some 100 hours in the calorimeter. This being the case it is inconceivable that the continuation of the experiment ever does them much harm. They are generally very lively at the end of an experiment. We see therefore that cold-blooded animals, remaining at rest and at constant temperature, give out heat at a uniform rate.

ii. *The effects of temperature upon the heat-production.*

In the experiments given in the following Tables it is necessary, from conditions of space, to omit all reference to the actual observations made with the galvanometer. I have given, at most, a very short description of each experiment, and have calculated the heat-production in every case in calories per c.c. of animal per hour. This process of calculation is described in my previous paper (*op. cit.*) and above. It should be noted that each recorded result is obtained from a series of observations extending over six or nine hours.

The temperature coefficient of the rate of heat-production is also given. The particular coefficient adopted is the ratio of the evolutions of heat for a difference of 10° C. If the rate of evolution at T° C. is v , and that at $(T+n)^{\circ}$ C. is v' , then the temp. coeff. is $\left(\frac{v'}{v}\right)^{\frac{10}{n}}$, and not, as is sometimes fallaciously assumed, $\frac{10}{n} \times \frac{v'}{v}$, or $\left\{1 + \left(\frac{v'-v}{v}\right)\frac{10}{n}\right\}$. This method of calculating the effect of temperature seems to be quite satisfactory.

In each experiment the results refer to the same batch of animals on the same day.

TABLE I.

Frogs; five to eight animals used for each experiment.

Exp. i.	July.	21.4° C.	H.P. = .57 cal. per c.c. per hour.
		19.1° C.	H.P. = .45 cal.
			Temp. coeff. = 2.7.
Exp. ii.	July.	27.2° C.	(a) .69, (b) .76, (c) .70 cal. per c.c. per hour.
		21.8° C.	(a) .54, (b) .51 cal.
			Mean temp. coeff. = 1.8.
Exp. iii.	July.	26.8° C.	(a) .92, (b) .64, (c) .88 cal. per c.c. per hour..
		18.5° C.	(a) .39, (b) .32, (c) .35 cal.
			Mean temp. coeff. = 2.7.
Exp. iv.	July.	28° C.	(a) .65, (b) .70 cal. per c.c. per hour.
		20° C.	(a) .44, (b) .49 cal.
			Mean temp. coeff. = 1.6.
Exp. v.	August.	28.6° C.	.92 cal. per c.c. per hour.
		26° C.	.56 cal.
		18° C.	(a) .43, (b) .56 cal.
		15° C.	(a) .21, (b) .20 cal.
			Choosing the observations at 15° C. and 28.6° C. as standards, temp. coeff. = 3.0.

TABLE I (*continued*).

Exp. vi.	Fresh frogs. October.
	23·2° C. ·79 cal. per c.c. per hour.
	17·6° C. ·67 cal.
	13·2° C. ·36 cal.
	9·3° C. ·29 cal.
	Choosing the observations at 9·3° C. and 23·2° C. as standards, temp. coeff. = 2·1.
Exp. vii.	Frogs kept in laboratory a month. October.
	21·6° C. ·40 cal. per c.c. per hour.
	18·4° C. ·27 cal.
	12·5° C. ·14 cal.
	Temp. coeff. = 3·1.
Exp. viii.	Frogs kept in laboratory a month. October.
	22·8° C. ·34 cal. per c.c. per hour.
	18·4° C. ·27 cal.
	13·4° C. ·17 cal.
	Temp. coeff. = 2·1.

The average value of the temperature coefficient is 2·4. The "mean probable error¹" of the result is \pm ·2.

TABLE II.

Snake: one animal used.

Exp. i.	Fresh, after one day in laboratory.
	16° C. ·34 cal. per c.c. per hour.
Exp. ii.	After two days in laboratory.
	23·5° C. ·55 cal. per c.c. per hour.
Exp. iii.	After four days in laboratory.
	11·4° C. ·15 cal. per c.c. per hour.
Exp. iv.	After five days in laboratory.
	10·5° C. ·23 cal. per c.c. per hour.

Plotting these in a diagram it is seen that the temperature coefficient is of the order of 2·7. The variations in the individual experiments (*e.g.* Exp. iii and iv) are too large for this to claim to be exact. Undoubtedly however the temp. coeff. is something of this order.

¹ See A. V. Hill, *This Journal*, XLII, p. 9. 1911.

TABLE III.

Newts: eight to ten animals used in each experiment.

All experiments made during October and November.		
Exp. i.	13·8° C.	·48 cal. per c.c. per hour.
	22·3° C.	·65 cal.
Temp. coeff. = 1·4.		
Exp. ii.	13·1° C.	·63 cal. per c.c. per hour.
	21·9° C.	·65 cal.
Temp. coeff. = 1·06.		
Exp. iii.	12·5° C.	·30 cal. per c.c. per hour.
	22·0° C.	·39 cal.
Temp. coeff. = 1·3.		
Exp. iv.	12° C.	·28 cal. per c.c. per hour.
	23° C.	·46 cal.
Temp. coeff. = 1·6.		
Exp. v.	13·0° C.	·28 cal. per c.c. per hour.
	21·1° C.	·47 cal.
Temp. coeff. = 1·9.		

The average value of the temperature coefficient for newts is 1·46.

From the experiments recorded above it is seen that temperature has a very large effect upon the heat-production of frogs and snakes, and a somewhat smaller effect upon that of newts. In the case of frogs the mean value of the temperature coefficient is 2·4, that is the heat-production of the intact animal is increased 2·4 times for a rise of 10° C. The greatest value recorded was 3·1, the least 1·6. In the case of the snake the temperature coefficient was of the order of 2·7: in that of newts the mean value was only 1·46, the highest recorded value being 1·9, the least 1·06. There is a threefold interest in these results:

(a) The values 2·4 and 2·7 for frogs and snakes are in general the same as the temperature coefficients of most chemical reactions: the living body seems to be merely a collection of chemical reactions, in which the rate of breakdown of certain unstable substances is increased two or three times by a rise of 10° C. These breakdowns must be quite apart from voluntary movements or muscular tone; the animals were sitting still, and tone is diminished by rise of temperature.

(b) The high value of the temperature coefficient shows how it is possible for cold-blooded animals to live for long periods in the cold without food. For example, a starving frog at 8° C. must give out only

some .1 cal. per gr. per hour, and at 3° C. only some .06 cal. In 100 days therefore at 8° C. the total heat-production amounts to only 240 cal. per gram, a quantity of heat which could be supplied by the oxidation of about $\frac{1}{18}$ gr. of carbohydrate or about $\frac{1}{40}$ gr. of fat.

(c) The lower value of the temp. coeff. in the case of newts suggests that in these animals there is some rudimentary reaction to fall of temperature. If this proves to be true, the method may afford a very useful way of following the development of the temperature-regulating-mechanism in the animal kingdom.

It has, of course, long been known that increased temperature causes increased rate of CO_2 -output¹. Regnault and Reiset² experimenting on three lizards found that at 7.3° C., 14.8° C., and 23.4° C. the CO_2 -evolution measured in c.c. per kilogram per hour was 12.6, 32.3 and 100.8 respectively, and the O_2 -intake 17.2, 45.2 and 134 respectively. Schulz³ working on summer frogs found the following numbers, reckoned as before in c.c. of CO_2 per kilo. per hour: 1° C., 5.1 c.c.; 1.5° C., 7.5 c.c.; 6.4° C., 34 c.c.; 15° C., 38 c.c.⁴; 25° C., 81 c.c.⁴; 33° C., 279 c.c.; 33.5° C., 340 c.c. In half-an-hour frogs' muscles go into rigor at 34.5° C., so the exps. at 33° C. and 33.5° C. are probably valueless: taking the rest, which owing to irregularities admit of only a very rough application, we find an approximate temperature coefficient of 2.3. The temp. coeff. of the CO_2 -production of the lizards is approximately 3.7. These numbers are of the same order of quantities as the temp. coeffs. of the heat-production—as indeed we should expect.

iii. *The effect of having O_2 in the calorimeter instead of air.*

A series of experiments was made with the purpose of determining the effect, if any, of allowing the animals to breathe O_2 in the calorimeter, instead of air. They are of course largely under water during the experiment, but in case there were any asphyxiation the presence of O_2 would tend to diminish it, and it is possible, though perhaps not probable, that the higher tension of O_2 , both in the air and water, would tend to increase the metabolism. In the experiments recorded below, made upon summer frogs, the heat-production is in every case "reduced" to 20° C. by means of the temperature coefficient⁵. This is necessary for the comparison, as the experiments were made at various temperatures.

¹ Moleschott. *Unters. z. Naturb. d. Mensch. u. d. Thiere*, II. p. 315. 1857.

² *Ann. de chim. et phys. sér. 3.* xxvi. Paris, 1849.

³ *Arch. f. d. ges. Physiol.* xiv. p. 78. 1877.

⁴ Mean of two exps.

⁵ Assuming the temp. coeff. to be 2.4 the "reduced" value is obtained by multiplying the value observed at n° C. by $(2.4)^{\frac{20-n}{10}}$.

TABLE IV.

(a) Experiments made on frogs in calorimeters containing O_2 , and in which O_2 was bubbled before each reading.

Number of Exp. ...	1	2	3	3	3	4	4	5
Temp. in $^{\circ}C$	21.4	19.3	21	22	21.5	21.8	21.5	22
H.P. per c.c. per hour ...	.57	.39	.61	.44	.61	.56	.42	.51
"Reduced" H.P. for $20^{\circ}C$.	.50	.41	.56	.37	.53	.48	.37	.43

The mean value of the "reduced" H.P. in the eight exps. is .46 cal. per c.c. per hour.

(b) Experiments made on frogs in calorimeters containing air, and in which air was bubbled before each reading.

For every experiment in (b) there is a corresponding experiment in (a), denoted by the same number, which was made the same day upon the same batch of frogs.

Number of Exp. ...	1	2	3	3	4	4	5
Temp. in $^{\circ}C$	19.4	19.4	21.8	21.6	21.3	21.8	21.5
H.P. per c.c. per hour ...	.45	.43	.60	.48	.51	.48	.54
"Reduced" H.P. for $20^{\circ}C$.	.47	.45	.51	.42	.45	.41	.47

The mean value of the "reduced" H.P. in the seven exps. is .45 cal. per c.c. per hour.

From the table we see that in O_2 the mean heat-production was .46 cal. per c.c. per hour, and in air .45 cal. No doubt this absolute equality is fortuitous: the table includes however all the experiments done on the subject, and the results were not worked out until the series was already complete. We see therefore that the presence of O_2 has no appreciable effect upon the heat-production of the frogs: we may conclude then (a) that in air they obtain a sufficient amount of O_2 and (b) that provided an animal has sufficient O_2 the presence of a higher tension of O_2 has no effect in quickening its normal resting metabolism. This is analogous to the old statement that a living cell is, within certain limits, independent of its surroundings, and will, if it be physically possible, regulate its metabolism to a fixed rate. Provided that the animal's tissues have sufficient O_2 , the presence of O_2 in a greater or less tension will have no appreciable effect upon the rate of oxidation of chemical substances in the tissues. This fact is exactly analogous to the case of a ferment action, in which the amount of substance to be transformed is large compared with the amount of ferment present. Under these conditions the action goes on at the same rate whatever, within limits, be the concentration of the reacting bodies. In particular, I have shown¹ that the rate at which yeast cells carry on their chemical actions, is independent (within wide limits) of the concentration of the cane sugar on which they are working.

¹ A. V. Hill, *This Journal*, XLIII. p. 283. 1911.

iv. *The heat-production of frogs kept without food.*

It is well known that frogs will live very long without food. It seemed therefore of interest to determine the effects of a prolonged fast, upon the rate of heat-production at a certain definite temperature. Fresh frogs were obtained and kept in the laboratory for a month: at intervals during this period their heat-production was determined. Fifteen frogs were used, three of which died during the course of the experiment. The rest remained perfectly active the whole time. They were kept at 16°C ., in clean water, in semi-darkness: seven or eight were used for each determination in the calorimeter. The experiment was begun on Oct. 14th, the same day as the frogs were brought into the laboratory. In nearly all cases an interval of a few hours was allowed, between the time of putting the frogs in the calorimeter and the first observation. This interval gave them time to settle down and become quiet before the observations (which usually extended over six to eight hours) began. For all the experiments, except those on the 23rd and 24th days, the same pair of flasks was used. The temperature of the frogs was always initially between 18°C . and 18.4°C .

TABLE V.

Number of day	...	...	1	2	4	5	7	10	14	15
Heat-production per c.c. per hour			.555	.46	.35	.41	.31	.33	.26	.29
Number of day	...	...	17	20	23*		24†		26	30
Heat-production per c.c. per hour			.30	.25	.24 .30		.26 .23		.27	.26

* On the 23rd day two exps. were made, at 12°C . and at 21°C .: the numbers given are "reduced," by means of the temp. coeff., to 18.2°C .

† On the 24th day two exps. were made, at 13.4°C . and at 22.8°C .: the numbers are "reduced" to 18.2°C .

The results recorded in this Table are shown graphically in Fig. 2. It is seen that in autumn frogs the heat-production at 18.2°C ., per c.c. of animal per hour, falls from its initial high value, 0.55 cal., to a certain lower one, about 0.26 cal. This fall takes place gradually, and is not complete for perhaps 15 days. After this time, however, the rate of heat-production seems to remain absolutely constant, without any further fall. The explanation is not easy to see. One might, of course, expect a certain fall as fasting proceeds: but in that case why should not the fall continue until the animal dies of inanition? Why

should the rate of heat-production decrease for awhile, only to remain constant later for a long period. Obviously some very fundamental change takes place, in the nature of the resting oxidations, between the time when the animal is fresh and the time when it is starving. It is not a question of mere activity: the frogs were very active at the end of 30 days. Possibly in the well-nourished animal there is an immediate store of energy (*e.g.* in the form of glycogen) in the muscles, which can be turned into heat: while in the fasting but active animal the energy has to be derived, directly or indirectly, from a more

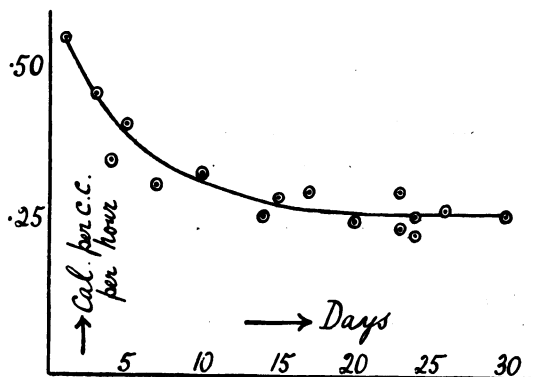


Fig. 2. Effects of fasting upon the rate of heat-production of frogs: the points shown \circ represent actual experiments. Horizontally, number of days fast: vertically, rate of heat-production per c.c. of frog per hour, at 18.2°C .

complicated chemical breakdown, such for example as the oxidation of fat. It is quite conceivable that when once an animal is reduced to the oxidation of fat it will work more economically than when it is oxidising carbohydrate. Such suggestions need testing, however, by work on the CO_2 -evolution¹ and O_2 -absorption, and on the actual quantities of certain chemical constituents in the fresh and starving frogs.

v. *The absolute values of the heat-production.*

The values given above are very various: they were made at different temperatures, upon frogs at various stages of fasting. From the previous

¹ *E.g.* a comparison of the evolution of CO_2 with that of heat should tell us at once whether the CO_2 and the heat are being derived from the oxidation of fat or from that of carbohydrate.

Tables the following results are collected, and "reduced" to the standard 20° C. by the aid of the temperature coefficient.

TABLE VI.

(A) Frogs.

(i) Heat-production per c.c. per hour of frogs fairly recently caught. 20° C.

·50, ·37, ·37, ·40, ·46, ·43, ·64, ·45, ·61, ·44, ·37, ·40, ·44, ·49, ·32, ·35,
·43, ·34, ·51, ·67, ·32, ·31, ·60, ·63, ·83, ·65, ·76.

The average value is

·48 cal. per c.c. of frog per hour.

(ii) Heat-production of frogs kept a month in the laboratory. At 18·3° C. this is about 0·26 cal., or "reduced" to 20° C.

·30 cal. per c.c. of frog per hour.

(B) Snake.

Heat-production "reduced" to 20° C. : four observations.

·48, ·40, ·32, ·53.

The average value is

·43 cal. per c.c. of snake per hour.

(C) Newts.

Heat-production "reduced" to 20° C. : 10 observations.

·61, ·62, ·82, ·61, ·40, ·36, ·38, ·41, ·36, ·45.

The average value is

·51 cal. per c.c. of newt per hour.

(D) Worms.

Two experiments only were done in this connection, on different batches of worms.

(a) At 15·6° C., ·21 cal. per c.c. of worms per hour.

(b) At 19·5° C., ·26 cal. per c.c. of worms per hour.

The experiment is not a very good one, as worms do not live well in water, and crawl about the whole time.

From the Table we see therefore that the heat-production is as follows:—

(a) Fresh frogs (*i.e.* not fasting more than 4 or 5 days) ·48 cal. per c.c. per hour, at 20° C.

(b) Frogs without food for 30 days, ·30 cal. at 20° C.

(c) Snake ·43 cal. at 20° C.

(d) Newts ·51 cal. at 20° C.

(e) Worms ·21 cal. and ·26 cal. at 15·6 and 19·5° C. respectively.

It is a striking phenomenon that the heat-productions of such different creatures as frogs, snakes and newts should all be of exactly the same order of size, viz. 0·5 cal. per c.c. of animal per hour at 20° C. The value for worms is somewhat less, but the experiment is not quite

satisfactory. It may be of interest to compare these numbers with values of the total energy degraded by various warm-blooded animals¹. From actual calorimetrical determinations, from the amounts of food eaten, and from the quantities of CO₂ given out and O₂ taken in, it is possible to obtain the following numbers: these are however only approximate. They are reckoned in calories per grm. of animal per hour.

Lion	0·8	Rabbit	6·0
Boar	1·6	Walrus	6·0
Elephant	1·8	Wapiti deer	6·0
Ox	2·0	Pigeon	6·0
Man	2·0	Rat	14·0
Dog	4·0	Mouse	22·0

A frog's muscle will, of course, go into heat rigor at 37° C.: we may however work out, by the aid of the temperature coefficient, what would be the evolution of heat by a frog at 37° C., were it not for this effect². The result is some 2·1 calories per grm. per hour. This is of the same order as the heat-production per grm. of most of the larger warm-blooded animals. At the same temperature the heat-producing activities of a mouse are 11 times as high as those of a frog; those of large warm-blooded animals however are no greater than, and may be less than, a frog's. In cold-blooded animals there is no need, or question, of the existence of a special heat-producing mechanism: all the heat that appears is the mere consequence of the ordinary chemical activities which are an accompaniment of every form of life. The fact that the heat-production per grm. of a frog, calculated for 37° C., is the same as that of a man or an ox, suggests that in the latter also there is no special heat-producing mechanism, but that their heat-production is only the immediate and necessary consequence of the chemical activities which must accompany their lives, as much as the life of a frog. Possibly the very much larger energy degradation in mice is due to greater muscular activity and to greater muscular tone: possibly however to specially developed heat-producing mechanism in the muscle.

The mean value of the heat-production of fresh frogs at 20° C. is ·48 cal. per c.c. per hour. This quantity of heat is equivalent to a

¹ By the courtesy of the Secretary of the Zoological Society of London I obtained an estimate of the diet of several large animals: the value for the mouse is from several experiments of my own not yet published: the rest are taken from *Schäfer's Text-Book of Physiol. Art.*, Pembrey, 1. p. 706 etc.

² It is possible experimentally to estimate the heat-production at 30° C.: extrapolation therefore to 37° C. is not a very unjustifiable proceeding.

combustion of either (i) .00012 gr. carbohydrate, or (ii) .000087 gr. protein, or (iii) .000052 gr. fat.

It would require in the three cases an absorption of O_2 of (i) .089 c.c., (ii) .125 c.c., (iii) .133 c.c. respectively: and a production of CO_2 of (i) .089 c.c., (ii) .085 c.c., (iii) .047 c.c. respectively.

It would be of great interest to compare the actual CO_2 -evolution and O_2 intake per gr. of frog with these values, in order to determine the actual nature of the oxidations occurring in the frog. From the experiments of Regnault and Reiset¹ on lizards, and of Schulz¹ on frogs, the CO_2 -evolution of lizards at 20° C. must have been about .07 c.c. per gr. per hour, and that of frogs about .056 c.c. per gr. per hour. These quantities are of the same order as the numbers derived above from the heat-production: for an exact comparison, however, parallel experiments are necessary.

The value of the temperature coefficient² given above suggests that the normal resting heat-production is due to certain chemical activities of the tissues, which are, like other chemical processes, quickened up by a rise of temperature. The heat-production cannot be, in the resting animal, merely due to muscular tone, to the activities of the heart, or to the contractions of unstriped muscle, for tone decreases within certain limits with rise of temperature, and the other factors are too small to account for much of the heat. Hence a large part of the heat-production of a resting animal depends on certain chemical activities of its tissues, which are essential in so far as they are a necessary accompaniment of life, but otherwise play no particular rôle in the more obvious and mechanical reactions of the animal. To take an analogy, it is necessary for the animal to keep a certain supply of explosive material ready, to explode on the provocation of an impulse: otherwise quick movements would be impossible. In the resting animal no such provocation occurs, but a rise of temperature increases the rate at which this unstable substance continually breaks down (not explosively) of its own accord, as it increases that of all chemical actions. The breakdown is not a direct combination with O_2 , for it is not quickened by the presence of O_2 at a higher tension. Such a view of the internal nature of the muscle

¹ *Loc. cit.*

² The indiscriminate use of the temp. coeff. to decide between chemical and so-called physical actions is to be deplored: most physiological processes lie in the borderland between the two. In this case the decision is between a chemical, or physico-chemical, action and an action depending upon the intermediation of the C.N.S., in fact a reflex production of heat. The latter type of action would probably be less intense at a higher temperature, owing to the loss of excitability and tone.

is in keeping also with other known facts, *e.g.* the CO_2 - and heat-production of resting isolated muscles, and the production of lactic acid in rigor, suddenly and explosively at 38°C . The decline in the rate of heat-production during fasting, to a certain constant value, is of interest when viewed in this light. Possibly in the fresh animal, with plenty of glycogen in its tissues, a higher concentration of this unstable body can be kept up than in the fasting animal, where the supply of the body has to be drawn from a complicated chemical transformation of fat into carbohydrate. The history of lactic acid and sugar would show that there is carbohydrate needed for the completion of this unstable body.

SUMMARY OF RESULTS.

Experiments have been made upon the total heat-production of four types of cold-blooded animals, *viz.* frogs, newts, worms and snakes. The method adopted was that of the differential micro-calorimeter described recently.

(1) The heat-production is, as one would expect, linear with the time: evidence is given to show that the animals are normal throughout the experiment.

(2) The rate of heat-production per gr. is practically identical for frogs, snakes and newts: it amounts to about .5 cal. per hour at 20°C .

(3) The presence of O_2 in the calorimeter has no effect different from that of air: the animal "regulates its own metabolism" independent of the O_2 tension, in the same way as the rate of heat-production by yeast cells is independent, within wide limits, of the concentration of the cane sugar in which they are working.

(4) The rate of heat-production of a frog or snake is increased 2 to 3 times by a rise of 10°C . This suggests that the normal resting heat-production is due to certain chemical activities of the tissues, which are, like other chemical processes, increased in rate 2 or 3 times by a rise of 10°C : the other possibility, *viz.* that the heat is due to certain reflex actions and tone, may be dismissed.

(5) It is possible to make direct observations on the heat-production of frogs, up to about 30°C . If, by means of the temp. coeff., the heat-production per gr. is calculated for 37°C . (neglecting the fact that heat rigor ensues at 35°C .) it is found to be the same as that of a man or other large warm-blooded animal, and much smaller than that of a small warm-blooded animal. The heat-production of men and big

animals is probably, therefore, not due to a special mechanism, but is merely a direct consequence of the activities of living cells.

(6) The rate of heat-production of a newt is increased only about 1.5 times by a rise of 10° C. Possibly this is due to the existence of some rudimentary form of heat-regulation.

(7) In frogs, fasting leads to a decline in the rate of heat-production : not an indefinite decline, but only to a certain constant value.

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