魚の心拍数,心拍出量および循環時間

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Heart Rate, Cardiac Output and Circulation Time of Fish*

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The role of the heart is to receive blood by expansion and to force it out by contraction. Heart rate, cardiac output and circulation time are the most important indices of the ability of the heart.

Heart Rate

Many determinations of the heart rate have been carried out with many species of fish, and are listed by DITTMER and GREBE[1], OZAKI[2], and so on. Considerable number of the determinations were done with the heart exposed or excised. Determinations under such unnatural conditions are not considered to give reliable figures. The heart rate of two freshwater fishes was determined in the present study, using the electrocardiogram recorded in conditions as near to natural as possible.

Material Rainbow trout, *Salmo gairdnerii irideus*, of 19–20 cm in fork length and 84–87 g in weight, and eel, *Anguilla japonica*, of 44–56 cm in total length and 110–230 g in weight, were used as the material.

Method Electrocardiogram of the rainbow trout was recorded through two electrodes, one fixed at the edge of an operculum and another fixed at the part just anterior to the dorsal fin. An uncovered tip (0.2 mm in diameter) of the earphone cord (1.0 mm in diameter) which was connected with a pen-writing electrocardiograph was used as the electrodes. Fish carrying the cord were able to swim around and were able to be kept

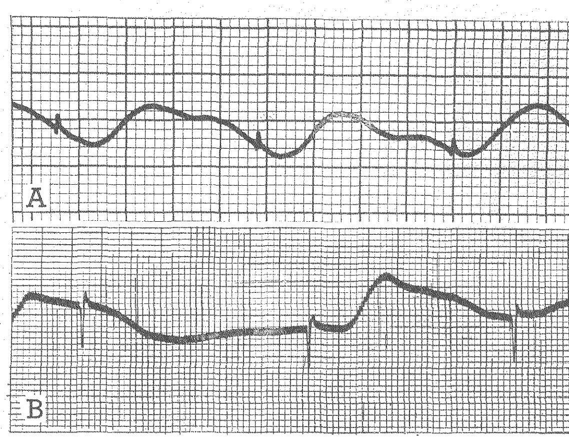

Fig. 1. Waves recorded by an electrocardiograph. A: rainbow trout, B: eel. Sharp waves are considered to be caused by contraction of the ventricle, and slow ones, simultaneous with the opercular movement, to be caused by the movement. Larger square shows 0.2 sec. by the horizontal side, and 0.25 mV by the vertical one.

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sound for several days in an experimental tank. An example of the electrocardiogram of the rainbow trout recorded by this method is shown in Fig. 1–A.

In the case of the eel, the method devised by YAMAMORI, HANYU and HIBIYA[3] was used with small modifications. An electrode was fixed at an anterior end of a plastic pipe of 2.7–4.1 cm in diameter and 45–50 cm in length, and another was fixed in a cut made at the middle of the pipe. When an eel creeps into the pipe from its habit, the electrocardiogram is recorded without any stimulus to the fish. An example of the electrocardiogram of the eel recorded by this method is shown in Fig. 1–B.

In both the cases of the rainbow trout and the eel, a small plastic tank of 45×31×22 cm was used as the experimental tank. The water was continuously renewed or aerated. Temperature and oxygen saturation of the water are important factors that influence the heart rate. Therefore, these factors were kept at optimum and almost constant levels, *i.e.*, 15–16°C in temperature and 84–95% in oxygen saturation in the case of the rainbow trout, and 21–24°C and 92–99% in the case of the eel.

Table 1. Heart rate and respiratory frequency of rainbow trout and eel

Fish		Water		Duration of experiment (hr:min)	Heart rate (/min.)			Resp. freq. (/min.)		
Length (cm)	Weight (g)	Temp. (°C)	O_2 (%)		Number of cases	Mean	S.D.	Number of cases	Mean	S.D.
				Rainbow trout						
20	84	15.2	89–92	1 : 00	5	51	6	5	78	7
20	87	14.9	84–88	3 : 00	7	49	5	7	75	4
19	87	15.7	84–93	7 : 00	14	42	9	14	77	11
19	86	16.2	88–95	4 : 50	13	42	3	13	97	4
					Total mean		46	Total mean		82
				Eel						
50	178	23.0		3 : 15	8	30	6	6	19	7
”	”	24.0	97–99	2 : 25	14	24	5	14	16	8
50	160	23.9	94–95	1 : 35	15	22	3	14	14	2
”	”	23.3	95–96	1 : 30	15	23	3	15	11	3
56	230	24.2	93	0 : 40	14	46	5	14	20	6
44	112	23.8	94–97	2 : 15	29	43	6	23	22	11
47	110	23.5	95–96	2 : 45	25	54	8	25	22	9
48	170	22.9	97–98	2 : 32	18	31	6	18	26	12
46	120	22.0	96–97	2 : 05	16	29	2	16	11	4
50	190	22.5	94–96	2 : 08	25	34	3	24	36	6
52	207	21.8	92–94	1 : 10	15	29	4	15	14	6
”	”	22.1	92–97	2 : 02	26	37	4	25	13	2
50	175	21.1	94–97	0 : 40	10	20	3	10	20	6
					Total mean		32	Total mean		19

Heart rate (beats/min.) was obtained by doubling the number of sharp and characteristic waves considered to be caused by beats of the ventricle for 30 seconds. The frequency of respiration also was determined, because respiration is closely related to circulation. It was determined from the waves recorded by the electrocardiograph that a rhythm, simultaneous with the opercular movement, existed on. The waves are shown in Fig. 1. At the same time, visual observation of the opercular movement also was used for the determination of the frequency of respiration.

Results The results are summarized in Table 1.

Cardiac Output

Cardiac output is properly to be calculated based on FICK's principle,

$$\text{Cardiac output (m}l\text{/kg, min.)} = \frac{\text{Rate of oxygen consumption (m}l\text{/kg, min.)} \times 100}{\text{Arterial oxygen (vol.\%)} - \text{Mixed venous oxygen (vol.\%)}} \qquad (1)$$

KOYAMA[4] calculated the cardiac output of carp by this formula. But there were few data on the oxygen content of the blood, because the determination of it was relatively difficult. MOTT[5], therefore, calculated the cardiac output of three marine fishes from the rate of oxygen consumption[6] and the oxygen capacity of blood[7] by the following formula,

$$\text{Cardiac output (m}l\text{/kg, min.)} = \frac{\text{Rate of oxygen consumption (m}l\text{/kg, min.)} \times 100}{\text{Oxygen capacity (vol.\%)}} \qquad (2)$$

In the formula (2), arterial blood is assumed to be fully oxygenated, and mixed venous blood to be completely deoxygenated. However, oxygen saturation of arterial blood is 65–85% in most cases[8], and mixed venous blood contains 1–3 vol.% of oxygen[9]. Therefore, the cardiac output calculated by the formula (2) may be lower than the actual value. MOTT[5] described the formula (2) to give a minimum figure for cardiac output. In the present paper, the cardiac output of three freshwater fishes and a marine one is calculated by the formula (1).

Material and Method The oxygen content of arterial and venous blood was quoted from the previous paper[9]. The fishes used in the work[9] were rainbow trout of 25–30 cm, 235–510 g, carp of 23–33 cm, 235–785 g, eel of 50–71 cm, 220–630 g, and *Oplegnathus fasciatus* (Oplegnathidae, Percina) of 27–29 cm, 750–880 g. Oxygen content of blood in the caudal vein is to be different from that of the mixed venous blood. But the former as well as the latter was utilized in the present work, because they showed no actual difference in the case of carp in the previous work. As the rate of oxygen consumption, the values determined in the conditions near to those in the present study were quoted from literature.

Results The results are summarized in Table 2.

Table 2. Cardiac output and circulation time in fishes

Species	O_2 cons. (m*l*/kg, min.)	Art. O_2 (vol.%)	Ven. O_2 (vol.%)	Cardiac output (m*l*/kg, min.)	Circulation time (min.)
Rainbow trout	1.50[10]	10.7[9]	1.3[9]	16.0	2.2
Carp	1.43[11]	8.0[9]	1.1[9]	20.7	1.7
Eel	0.75[12]	6.7[9]	2.7[9]	18.8	1.9
Oplegnathus	2.60[11]	9.4[9]	2.3[9]	36.6	1.0

Circulation Time

Mean total circulation time is given by the following formula,

$$\text{Circulation time (min.)} = \frac{\text{Total blood volume (m}l\text{/kg)}}{\text{Cardiac output (m}l\text{/kg, min.)}} \qquad (3)$$

Little work has been done in order to estimate the mean total circulation time in fish. MOTT[5] calculated it in *Opsanus tau* by the above-mentioned formula. In the present paper, the mean total circulation time in the four fishes described in the foregoing section is estimated by the same method.

Material and Method Description on the material and a part of the method is omitted, because the data in the foregoing section are used in the present one too. The total blood volume (m*l*/100 g of body) was reported to be 3.5 in *Salmo gairdnerii*[13], 2.5–3.0 in *Carassius carassius*[14], and 4.0–5.9 in *Belone vulgaris*[14]. The value was roughly assumed to be 3.5 in all fishes used in the present study.

Results The results are summarized at the right end of Table 2.

Discussion

The heart rate (beats/min.) of the rainbow trout of 84–87 g was 42–51 (the mean 46) in the conditions, 15–16°C and 84–95% of oxygen saturation. These values are slightly higher than those in *Salmo fario* by BIELIG[15]. He showed the figures of 30–46 with excised heart of the fish in 16–20°C. The heart rate of the eel of 110–230 g was 20–54 (the mean 32) in the conditions, 21–24°C and 92–99% of oxygen saturation. BIELIG[15] showed the figures of 48–56 with excised heart of *Anguilla vulgaris* in 16–20°C. GITTER[16] showed the figures in intact *Anguilla vulgaris* to be 23 at 12°C, 27 at 20°C, and 96 at 30°C. The values obtained in the present study are lower than that at the same temperature estimated from the data by BIELIG, and at almost the same level as that estimated from the data by GITTER.

The heart rate of the rainbow trout (46) or the eel (32) is much lower than that of homoiothermal animals, *e.g.*, man of 20 years old (71)[1], dog of 20 kg (85)[1], or chicken of 1 kg (354)[1], and at almost the same level as that of other poikilothermal animals, *e.g.*, crocodile (30 at 15°C)[1], or frog (34–39 at 22°C)[1].

The cardiac output (m*l*/kg, min.) was estimated to be 16.0 in the rainbow trout, 20.7 in the carp, 18.8 in the eel, and 36.6 in *Oplegnathus*. These values are a little larger than 4.5–13.2 in the carp reported by KOYAMA[4], and 13.7 in *Stenotomus chrysops*, 15.5 in *Tetraodon maculatus*, and 10.1 in *Opsanus tau* reported by MOTT[5]. The small values in the last three species may be related with the relatively sluggish habit of the fishes, though they may be partly attributed to the estimating method.

The cardiac output of fishes may be roughly concluded to range from 10 to 35. These values are much smaller than that of mammals, *e.g.*, 85 in man[1], or 137 in dog[17].

The mean total circulation time (min.) was estimated to be 2.2 in the rainbow trout, 1.7 in the carp, 1.9 in the eel, and 1.0 in *Oplegnathus*. These values are at almost the same level as 2.2* in *Stenotomus*, 1.9* in *Tetraodon*, or 2.0[5] in *Opsanus*, and larger than that in mammals which is estimated to be less than 1 min.

The tissues of fish are considered to receive much smaller amount of blood in a given time compared with mammals. Moreover, the oxygen content of the blood supplied to the tissues is much smaller in the former than in the latter. Therefore, the tissues of fish are concluded to receive much smaller amount of oxygen in a given time compared with mammals. The higher percentage of oxygen utilization in fishes reported in the previous paper[9] is considered to be an adjustment to this condition.

Summary

1. Heart rate (beats/min.) determined from electrocardiogram recorded in conditions as near to natural as possible was 42–51 (the mean 46) in the rainbow trout, and 20–54 (the mean 32) in the eel.

2. Cardiac output (m*l*/kg, min.) estimated by FICK's principle was 16.0 in the rainbow trout, 20.7 in the carp, 18.8 in the eel, and 36.6 in *Oplegnathus*.

3. Mean total circulation time (min.) estimated from the cardiac output and the blood volume was 2.2 in the rainbow trout, 1.7 in the carp, 1.9 in the eel, and 1.0 in *Oplegnathus*.

4. Tissues of fish are considered to receive much smaller amount of blood in a given time compared with mammals.

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* Estimated from the cardiac output by MOTT[5] and the total blood volume which was arbitrarily assumed to be 3.0 m*l*/100 g of body.

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