Influence of the Annual Change of Field Temperature on Active Metabolism in Cultured Red Sea Bream

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To clarify the influence of annual change of field water temperature on the active metabolism in cultured red sea bream, oxygen consumption was measured monthly throughout the year at various swimming speeds ranging from 0 BL/s to 3 BL/s. The measurements were made from April 1993 to April 1994 at experimental temperatures close to those occurring normally in the nearby fish farm.

The change of active metabolism with the increase of swimming speed showed a mountainous pattern under 1.25 BL/s, with a small peak near 1.00 BL/s, which became higher with increased field temperature. Within the range from 1.25 BL/s to 2.00 BL/s, the change exhibited logarithmically a parallel pattern and the slope of relationship between both values became smaller with the increase of field temperature. Furthermore, the change of slope with field temperature followed different loci with season changes toward warmer weather and colder weather, and it followed a marked counter clockwise pattern. Therefore, though the field temperature was approximately the same, the slope was lower in season tending toward warmer weather than in season tending toward colder weather. Above 2.00 BL/s, the change leveled off for all months as compared with that within the range from 1.25 BL/s to 2.00 BL/s.

Key word ; Cultured red sea bream, Resting metabolism, Annual field temperature

The adaptation mechanism in fish of a poikilotherms animal to the environmental water temperature has already been reported by many authors in relation to enzymatic activity,[1-5] respiratory movement,[6] and respiratory metabolism of resting,[7-12] and active[13-15] condition among fish species differing in habitat temperature and for the same fish acclimated to different temperatures.

Regarding the active metabolism in these findings, Brett[16] had measured the active metabolism in relation to swimming speed at 5, 10, 15, 20 and 24℃ in sockeye salmon acclimated at desired temperature for at least two weeks. He had reported that active metabolism increased exponentially with the increase of swimming speed at all of the acclimation temperatures, and also that the slopes of the relationship between the swimming speed and the active metabolism became smaller with the increase of acclimation temperature. Duthie,[17] however, had determined the active metabolism during various swimming activities in three flatfish species acclimated at 5, 10, and 15℃ for two months, and he had found that not only the level but also the slope exhibited relatively steady value among three species and among three acclimation temperatures, though the active metabolism increased semilogarithmically with the increase of swimming speed all of three species as same as the finding by Brett.[16] This is contrary to the findings by Duthie, Bernatchez *et al.*,[18] who measured the active metabolism during various swimming performances in cultured lake whitefish and wild cisco acclimated at 5, 12, and 17℃ for one week, and found that the slope was larger at 5℃ than at 12 and 17℃, and also the slope at the same acclimation temperature was smaller in cultured lake whitefish than in wild cisco.

Under field conditions and in the same fish species, however, the studies on active metabolism in relation to the annual change of field temperature have scarcely been researched. Therefore, the present study was undertaken to clarify the influence of the annual change of water temperature on active metabolism of cultured red sea bream, in order to estimate the annual change of active metabolism under field situation conditions.

Materials and Methods

Sample Fish

We used cultured red sea bream, *Pagrus major* of commercial size, which were cultivated by a fish farmer in Tachibana Bay, Nagasaki prefecture. Four specimens were purchased per month during one year from April 1993 to April 1994 excepting August, September 1993, February and March 1994, with a total of sample fish of 36 specimens throughout the year. To recover from the effect of transfer, the sample fish were held in a 500l FRP tank with water at the experiment temperature for 10 days before starting the experiment. They were fed daily moist pellets, and starved for 24 h before starting the experiment.

Field and Experiment Temperatures

The temperature of sea water nearby the fish farm in the bay was measured daily at 10:00 a.m. at 1 m depth and the mean value of water temperature each month was calculated as the field temperature. Concerning to the temperature of sea water in the bay, it had already been determined that the difference of water temperature between the surface and bottom is very small throughout the year, because the water depth in the bay is very shallow.

Experimental temperature on the other hand was the mean water temperature over the 14 days before the sampling date, and oxygen consumption of fish measured at this temperature.

Measurement of Resting and Active Metabolism

The oxygen consumption of sample fish under resting conditions was measured with the same equipment as our original work as shown in Fig. 1, according to the procedure of Wu *et al.*.[19] The fish was gently fitted into a mobile fish holder in the respiration chamber and was held to take a resting condition. Oxygen consumption was measured at the experiment temperature by monitoring the depletion of dissolved oxygen concentrations in the respiration chamber with a D.O. meter (YSI, Model 58) and recorder (Pantos Nihon Denshi Kagaku). The measurement was done continuously for at least 1 h. The resting metabolism was calculated by using partially a stable oxygen consumption more than 30 or 60 min and was expressed in units per the actual body weight per hour (mg O_2/kg·h).

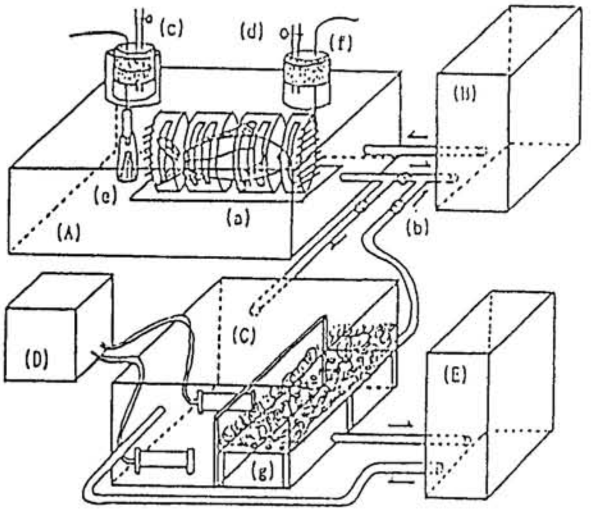

Fig. 1. The equipment for measuring the oxygen consumption of fish under resting condition. The fish is gently fitted into a mobile fish holder (a) in the main chamber (A) full of almost air-saturated sea water. Air bubbles in the sea water are removed from the upper tube (c and d) and the sea water is controlled at a constant temperature by a thermoregulator (B). The oxygen consumption of fish under resting condition is measured by D.O. meter (YSI, Model 58) (e), and the pH value of sea water is checked by a pH sensor (f). In continuous measurement for a long time, sea water in the reservoir chamber (C) is saturated with air by the air pump (D) and is controlled at a constant temperature by another thermoregulator (E). When starting continuous measurement, sea water in the main chamber is exchanged through the synthetic wool filter (g) with sea water in the reservoir chamber by opening the valves (b).

The oxygen consumption of sample fish under active metabolism was measured with a circulating water system designed for swimming as shown in Fig. 2. The fish was gently put into the swimming chamber and was kept free for at least 4 h until the fish recovered from the effect of handling stress. Thereafter, the fish was started swimming at low water velocity of 5 cm/s, and the water velocity increased gradually in steps at intervals of about 5 cm/s until reaching the experimental water velocity. Oxygen consumption under active conditions was measured at the exper-

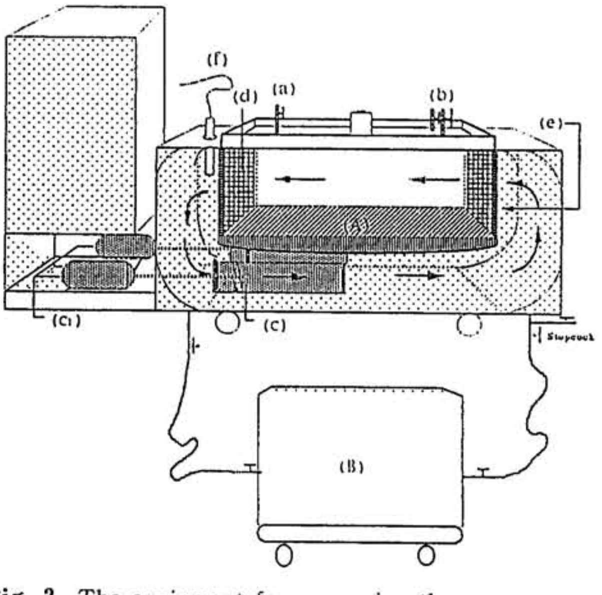

Fig. 2. The equipment for measuring the oxygen consumption of fish under active conditions. The fish is gently put into swimming chamber (A) full of almost air-saturated sea water. Air bubbles in the sea water are removed from the upper tube (a and b), and the water temperature and water velocity are controlled under constant conditions by a thermoregulator (B) and by two impellers (c) connecting to a velocity regulator (c_1), and two honeycomb grids (d and e), respectively. The oxygen consumption of fish under active conditions is measured by D.O. meter (YSI, Model 58) (f).

imental temperature each month and at various water velocities by monitoring the depletion of dissolved oxygen concentrations in circulating water (180*l*) with a D.O. meter and a recorder. Measurement was done continuously for at least 30–60 min and with a level of oxygen concentration above approximately 50% air saturated. The active metabolism was calculated by using partially a stable oxygen consumption of more than 20 min and was expressed in units per the actual body weight per hour (mg O_2/kg·h). The active metabolism was measured at various swimming speeds: namely 1.00, 1.25, 1.50, 1.75, 2.00, 2.50, and 3.00 BL/s, and were expressed in a unit of multiples of standard body length per second. After measuring at each swimming speed, the sample fish was rested in still water for at least 30 min, and at the same time oxygen concentration in circulating water was saturated by the air pump.

Results

Body Size of Sample Fish

The monthly mean values and standard deviation of standard body length and body weight on sample fish are shown in Table 1. The standard body length and body weight of fish specimens ranged from 25.8 cm to 29.5 cm and from 509.6 g to 773.5 g throughout the year, respectively. The variation of body length and weight was slightly different among fish specimens. The mean values tended to be smaller in April, May and July 1993 than in the other months. The mean values were fairly good approximations, however, with the exception of April, May and July.

Annual Change of Field and Experiment Temperature

The monthly value of field temperature increased gradually from April 1993 at 15.5±0.3℃ in the beginning of the experiment to 25.0±1.0℃ at maximum in August 1993, and decreased gradually again toward a minimum in February 1994 at 12.1±0.4℃. Temperature subsequently increased again toward April 1994 at 15.2±0.5℃.

Monthly changes in experimental temperature approximated the above annual change of field temperature despite slight differences (Table 1). The ranges of those annual changes were 12.9℃ at the field temperature and 12.0℃ at the experimental temperature, respectively.

Change of Active Metabolism with Swimming Speed

The change of active metabolism with swimming speed ranging from 0 BL/s under resting conditions to 3.00 BL/s under active conditions is shown in Fig. 3 by each month. The change of active metabolism did not show parallel that of swimming speed at all ranges from 0 BL/s to 3.00 BL/s. Namely, the change within the range from 0 BL/s to 1.25 BL/s showed a peak as the level of active metabolism was higher at 1.00 BL/s and lower at 0 BL/s and 1.25 BL/s, and in the range above 1.25 BL/s, the level increased linearly, showing a parallel pattern. In the range above 2.00 BL/s, however, the level increased somewhat slowly toward 3.00

Table 1. Collection date, field temperature, experimental temperature, specimen number, standard body length, and body weight on cultured red sea bream used in the present study

Collection date			Field temperature: Monthly mean (℃)	Field temperature: Mean for two-weeks before collecting (℃)	Experimental temperature (ET) (℃)	Specimen number	Mean and Standard deviation. Standard body length (cm)	Mean and Standard deviation. Body weight (g)
Apr.	20,	1993	15.5±1.3	14.9±0.9	15	4	26.58±0.66	629.23±35.70
May.	27,	1993	18.2±0.9	18.6±0.4	18	4	27.22±1.20	571.69±54.53
Jun.	21,	1993	21.1±0.7	21.3±0.6	22	4	28.26±0.97	653.75±50.97
Jul.	31,	1993	22.7±1.2	23.4±0.3	25	4	29.88±1.19	636.54±28.71
Aug.		1993	25.0±1.0	–	–	–	–	–
Sep.		1993	23.9±0.6	–	–	–	–	–
Oct.	26,	1993	21.6±1.0	21.8±0.7	21	4	28.80±0.91	663.18±40.45
Nov.	30,	1993	19.5±1.3	18.1±0.8	18	4	28.70±0.35	695.78±42.77
Dec.	30,	1993	15.4±1.3	13.8±0.4	15	4	29.20±0.67	694.20±29.93
Jan.	31,	1994	13.0±0.9	12.2±0.6	13	4	28.73±0.96	708.90±59.93
Feb.		1994	12.1±0.4	–	–	–	–	–
Mar.		1994	12.5±0.5	–	–	–	–	–
Apr.	17,	1994	15.9±1.2	15.2±0.5	15	4	28.45±0.64	657.78±36.16
Total						36	28.36±1.37	634.99±101.97

These sample fish of market size were obtained monthly from a fish farmer at Tachibana Bay in Nagasaki Prefecture for a year from April 1993 to April 1994. The field temperarture at a depth of 1m in the fish culture area was measure daily at 10:00 a. m.

BL/s. These tendencies appeared throughout the year and were more clear in the summer months than in the winter months.

On the comparison by month of the level of active metabolism, the level was the highest in July at the maximum experimental temperature 25℃ and was the lowest in January at the minimum experimental temperature 13℃ within the range from 1.25 BL/s to 2.00 BL/s (Fig. 3). Furthermore, the annual change of active metabolism at the same swimming speed showed a pattern parallel to that of experimental temperature (Fig.4).

Change of Active Metabolism under 1.25 BL/s

The change of active metabolism with swimming speed under 1.25 BL/s is newly shown in Fig. 5. We applied a parabola to the change of a peak pattern using the following equation : $AM = a + bS + cS^2$, in which variables AM and S and constants a, b, and c expressed active metabolism (mg O_2/kg.h), the swimming speed (BL/s), and parameters of a,

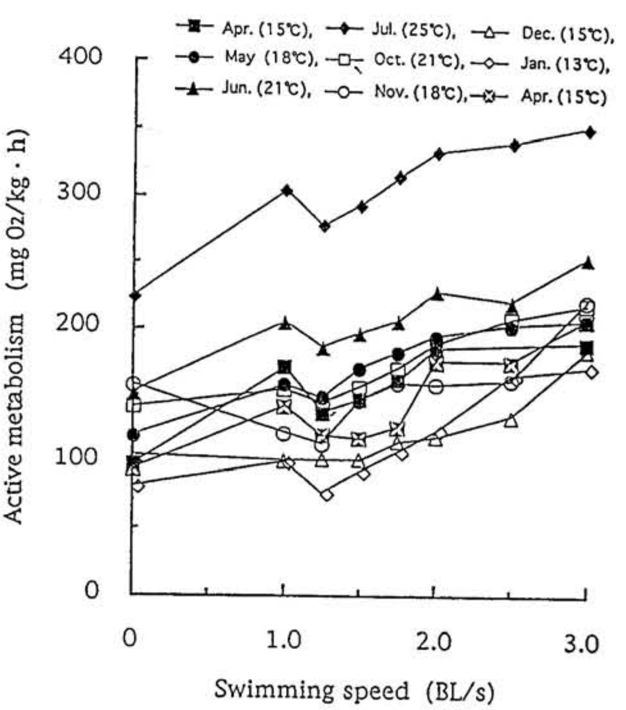

Fig. 3. The change of active metabolism with the increase of swimming speed by month in cultured red sea bream. The temperature in parentheses expresses the experimental temperature of each month.

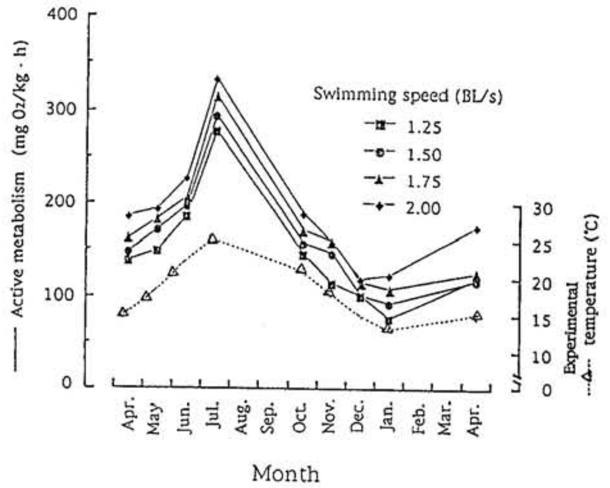

Fig. 4. The monthly change of active metabolism in cultured red sea bream at 1.25, 1.50, 1.75, and 2.00 BL/s and the monthly change of experimental temperature.

Table 2. Collection date, specimen number, experimental temperature, and parameters of the equations of the parabolic relationship between swimming speed and active metabolism (AM) in the range O BL/s to 1.25 Bls in cultured red sea bream

Collection date	Specimen number	Experimental temperature (ET) (℃)	Relationship between swimming speed and AM a	b	c
Apr. 20, 1993	4	15	98.535	239.160	−165.902
May. 27, 1993	4	18	120.611	99.226	−61.144
Jun. 21, 1993	4	22	152.347	154.399	−102.013
Jul. 31, 1993	4	25	223.866	232.541	−150.912
Aug. 1993	−	−	−	−	−
Sep. 1993	−	−	−	−	−
Oct. 26, 1993	4	21	142.178	55.562	−42.630
Nov. 30, 1993	4	18	158.007	−36.318	1.286
Dec. 30, 1993	4	15	104.824	−6.845	3.659
jan. 31, 1994	4	13	81.338	110.370	−91.192
Feb. 1994	−	−	−	−	−
May. 1994	−	−	−	−	−
Apr. 17, 1994	4	15	94.310	156.368	−108.131
Total	36				

b, and c, respectively. The parabola is illustrated in Fig. 5 and the value of each parameter is shown in Table 2 by month. The parabola was in conformity with the experimental values for each month, and took the maximum value of active metabolism around 0.75 BL/s excluding November and January. The mountainous pattern was more gently sloping in the winter months than in the summer months.

On the other hand, the value of parameter a, which expressed resting metabolism, changed in parallel with the experimental temperature though the locus differed slightly at the two season changes toward warmer weather and colder weather (Fig.6). We applied two parabolas to the loci using the following equation: $a1 = 194.416 - 18.268\ ET + 0.769\ ET^2$ for the season change toward warmer weather and $a_2 = 1.200 + 4.336\ ET + 0.171\ ET^2$ for the season change toward colder weather, where the values of a and ET express the resting metabolism (mg O_2/kg.h) and experimental temperature (℃), respectively. The values of parameter b and c varied out of parallel with the experimental temperature and these took the minimum level or the maximum level around 18℃ of experimental temperature though the locus differed between two season changes toward warmer weather and colder weather. We applied two parabolas to the loci for each parameter using the following equation: $b1 = 505.180 - 42.317 + 1.233\ ET_2$ and $c1 = -471.261 + 41.3832\ ET - 1.131\ ET_2$ for the season change toward warmer weather, and$b_2 = 1601.576 - 18.704\ ET + 5.133\ ET_2$ and $c_2 = -1023.695 + 114.613\ ET - 3.198\ ET_2$ for the season change toward colder weather.

Change of Active Metabolism above 1.25 BL/s

The change of active metabolism with swimming speeds above 1.25 BL/s showed a linear pattern (Fig. 3). Therefore, the relationship between the swimming speed and active metabolism is newly shown in Fig. 7. The relationship

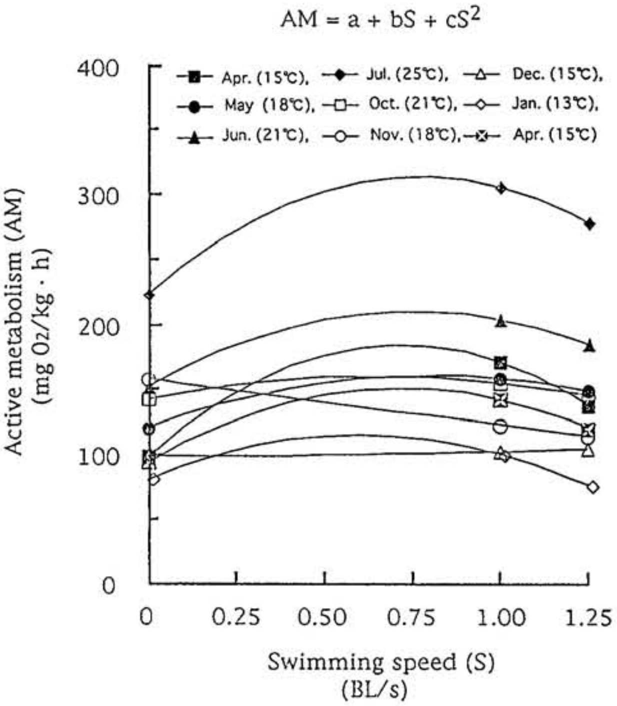

Fig. 5. The change of active metabolism in cultured red sea bream with the increase of swimming speed in the range from 0 BL/s to 1.25 BL/s for each month. The curves express parabola applied to the change of active metabolism with the increase of swimming speed as using the equation of $AM = a + bS + cS^2$. The temperature in parentheses is the same as Fig. 3.

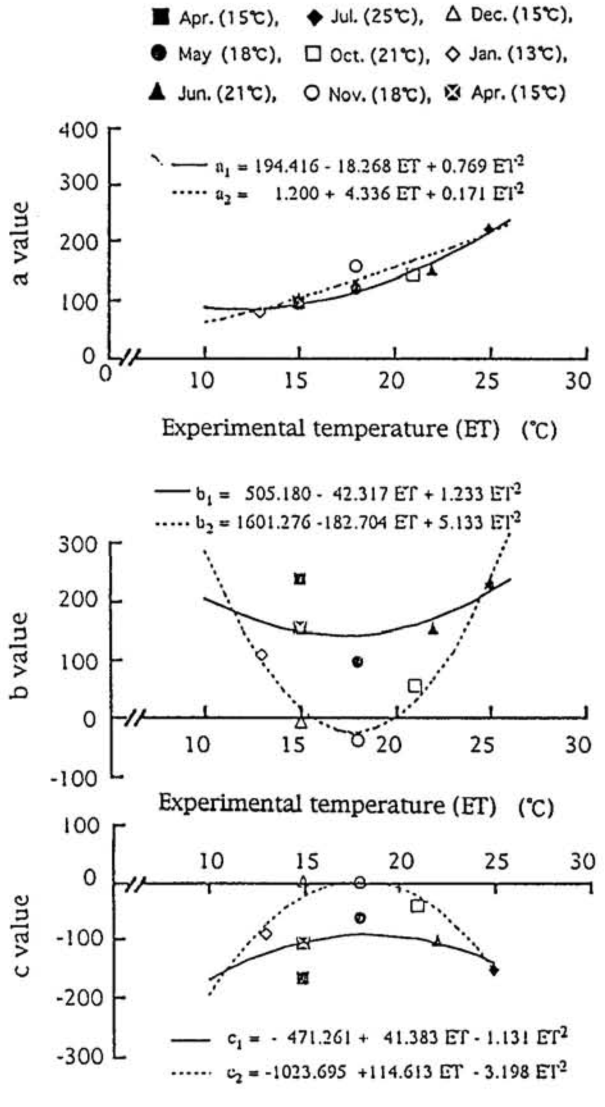

Fig. 6. The relationship between the experimental temperature and each of the parameters of a parabola applied to the change of active metabolism with the increase of swimming speed. a, b, and c express parameters of a parabola calculated by using the equation, $AM = a + bS + cS^2$ as shown in Fig. 5. The temperature in parentheses is the same as Fig. 3.

showed a linearly positive correlation throughout the range from 1.25 to 2.00 BL/s. So, we applied a linear equation to the relationship using the following equation: AM=dS+f, where the variables AM, S, d, and f expressed the active metabolism, the swimming speed, and parameters d and f, respectively. The correlation was significant for all months excluding November, December, and April 1994 (Table 3). Values of active metabolism above 2.00 BL/s, however, were distributed at short distance below a production of the regression line, and then the residual value became larger with the increase of swimming speed. This tendency appeared throughout the year and was more clear in summer months than in winter months.

On the other hand, the values of slope (d) and intercept (f) were plotted against the monthly experimental temperature as shown severally in Fig. 8. The value of slope (d) generally became smaller with the increase of experimental temperature, excepting July and December. The locus of the change, however, differed between the season changes toward warmer weather and colder weather, and then the value slight higher in the months of the warmer season than in the months of the colder season, even though experimental temperatures were approximately the same. We applied two parabolas to the loci of season changes using the following equation: slope (d_1) $=176.880-12.728$ ET$+0.339$ ET_2 for the season change toward warmer weather and slope (d_2) $=158.647-13.506$ ET$+0.409$ ET_2 for the season change toward colder weather, where the variable ET ex-

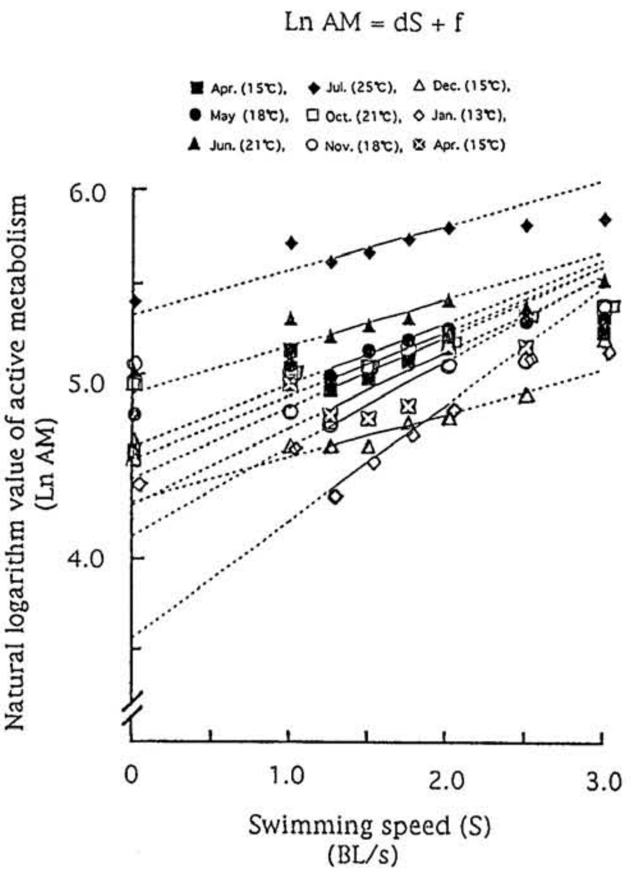

Fig. 7. The relationship between the swimming speed and the natural logarithm value of active metabolism in the range from 1.25 BL/s to 2.00 BL/s in cultured red sea bream for each month. A solid line expresses the regression line between both values as using the equation of Ln AM=dS+f for each month, and a dotted line expresses a production of regression line. The temperature in parentheses is the same as Fig. 3.

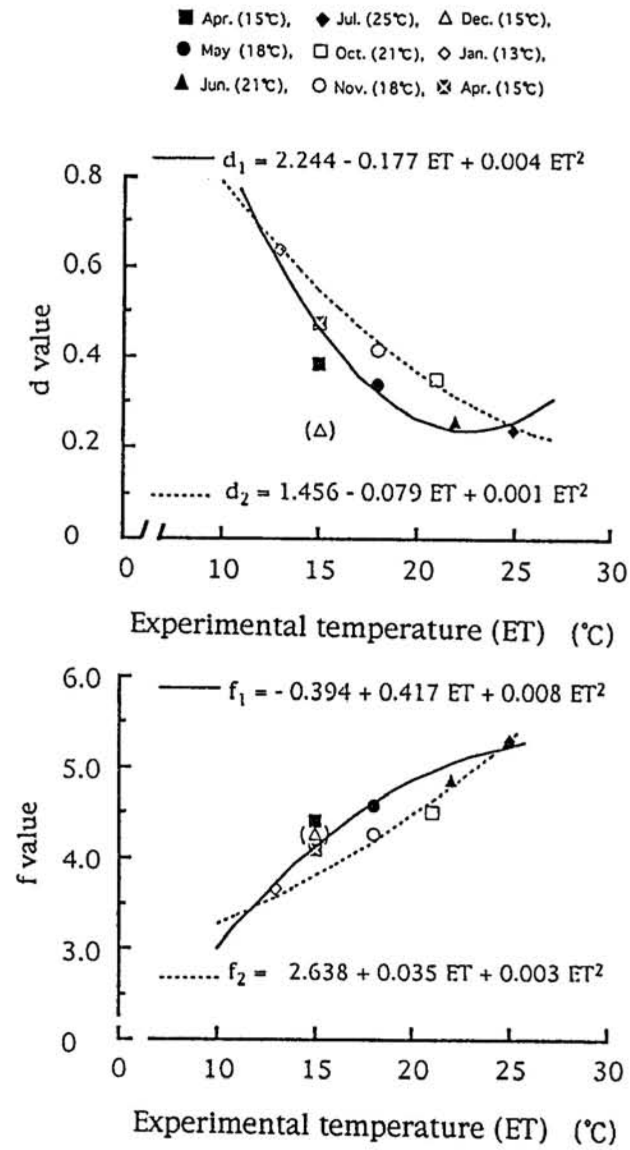

Fig. 8. The relationship between the experimental temperature and each parameter of slope and intercept of a exponential equation applied to active metabolism with the increase of swimming speed within the range from 1.25 BL/s to 2.00 BL/s. The solid and dotted curves express parabolas calculated between both values by each of season changes toward warmer weather and toward colder weather, respectively. The temperature in a parentheses is the same as Fig. 3.

Table 3. Collection date, specimen number, experimental temperatue, resting metabolism, parameters, and coefficients of correlation of the relationshipbetween swimming speed and natural logarithm value of active metabolism(AM), and resting metabolish(RM) estimated from intercept in cultured red sea bream

Collection date	Specimen number	Experimental temperature (ET) (℃)	Resting metabolism ($mg\ O_2/kg \cdot h$)	Relationship betwen swimming speed and AM				RM estimated from intercept ($mg\ O_2/kg \cdot h$)
				n	slope(d)	intercept(f)	r	
Apr.20, 1993	4	15	98.535	4	0.390	4.425	0.988※	83.513
May27, 1993	4	18	120.611	4	0.344	4.597	0.978※	99.186
Jun.21, 1993	4	22	152.347	4	0.262	4.891	0.986※	133.087
Jul. 31, 1993	4	25	223.866	4	0.243	5.325	0.999※※※	205.408
Aug. 1993	–	–	–	–	–	–	–	–
Sep. 1993	–	–	–	–	–	–	–	–
Oct.26, 1993	4	21	142.178	4	0.354	4.530	0.999※※※	92.758
Nov.30, 1993	4	18	158.007	4	0.420	4.285	0.875 N.S.	72.603
Dec.30, 1993	4	15	104.824	4	0.242	4.303	0.934 N.S.	73.921
Jan.31, 1994	4	13	81.338	4	0.642	3.555	0.997※※	34.813
Feb. 1994	–	–	–	–	–	–	–	–
Mar. 1994	–	–	–	–	–	–	–	–
Apr.17, 1994	4	15	94.310	4	0.479	4.118	0.836 N.S.	61.436
Total	36							

N.S.=Non significant, ※$p<0.05$, ※※$p<0.001$, and, ※※※$p<0.001$

presses the experimental temperature. These parabolas were in good conformity with the values of slope (d). The value of intercept (f) became larger with the increase of experimental temperature on the whole, contrary to the case of slope (d). The locus of the change too, differed between the season changes toward warmer weather and colder weather. The value of intercept (f) was larger in months of the warmer season than in months of the colder season, contrary to the case of slope (d), though the experimental temperature was approximately the same. We applied two parabolas to the loci of season changes using the following equation : intercept (f_1) $=-141.521+9.984\ ET+0.111\ ET_2$ for the season change toward warmer weather and intercept (f_2) $=165.178-23.478\ ET+0.956\ ET_2$ for the season change toward colder weather, where the variables ET and intercept (f) express the experimental temperature and the natural logarithm value of resting metabolism, respectively. The conformity of the parabola to the parameter values was inferior to the case of slope (d). The value of resting metabolism estimated from the intercept value (f) was much smaller than the measurement value for all of the months (Table 3).

Discussion

The change of active metabolism with slow swimming speeds (under 1.25 BL/s) showed a nonparallel pattern to that of swimming speed and a peak pattern as the level was higher in 1.00 BL/s than in 0 BL/s and 1.25 BL/s for all of the months. The change of active metabolism within the range from 1.25 BL/s to 2.00 BL/s, on the other hand, showed a pattern parallel to that of swimming speed (Fig. 3, 5 and 7). No abnormal condition was observed in the water current under 1.25 BL/s in the swimming chamber, and the sample fish in the swimming chamber continued swimming steadily at both 1.00 BL/s and 1.25 BL/s. Parsons and Sylvester[20] have examined oxygen consumption at various swimming speeds in white crappie of 89～96 g wet mass and 165～175 mm standard body length and they observed an unexpected decrease in oxygen consumption at water velocity 20～25 cm/s, coinciding approximately with the change from labriform to caudal locomotion. Furthermore, they had found that the swimming efficiency was optimal at 20–25 cm/s. Freadman[21] also had report a similar tendency in striped bass and bluefish. On the other hand, in human beings, it has been already reported that the working metabolism was at a minimum at a certain intensity of work for various tasks, which is to say, the level of working metabolism rises not only for higher intensities of work, but also at intensities lower than in this value.[22] Therefore, regarding this result, it was conjectured that active metabolism reaches a minimum level at swimming speeds near 1.25 BL/s, indicating that swimming efficiency could be optimal near 1.25 BL/s in cultured red sea bream.

Within the range from 1.25 BL/s to 2.00 BL/s, the level of active metabolism increased logarithmically with swimming speed, showing a positive correlation for all months (Fig. 7). This tendency agreed with findings in sockeye salmon by Brett[16] and in white crappie by Parsons and Sylvester[20] though their range of swimming speeds was different. Furthermore, the slope value of the relationship between the swimming speed and the active metabolism became smaller with the increase of field temperature toward warmer weather and became larger with the decrease of field temperature toward colder weather (Fig. 8). Brett[16] and Kruger *et al.*[23] also reported a similar findings. The change of slope with field temperature exhibits different loci in season changes toward warmer weather and colder weather, and the annual change of slope followed a markedly counter clockwise pattern. Therefore, though the field temperature was approximately the same, the slope value was smaller in months tending toward warm weather than in the months tending toward cold weather. This tendency agrees with the pattern of annual change of resting metabolism in cultured red sea bream.[24] The relationship in the case of active metabolism, however, showed a negative correlation in contrast to the case of resting metabolism. This result suggests that the change of slope precedes the change of annual field temperature. In other words, the response of cultured red sea bream was exhibited in the quick slope relative to the annual change of field temperature. On the other hand, the change of intercept value with the field temperature showed a positive correlation in contrast to the case of slope. The loci toward the two season changes (Fig. 8) were also contrary. The value of resting metabolism estimated from intercept values was much smaller than the measurement value for all of the months (Table 3). This result suggests that the level of resting metabolism does not correlate with the product of a relationship between the swimming and the active metabolism.

In the range above 2.00 BL/s, the change of active metabolism with swimming speed increased relatively slowly toward 3.00 BL/s compared with the range from 1.25 BL/s to 2.00 BL/s (Fig.3 and 7). Therefore, the level of active metabolism was distributed at short distance below the product of a regression line between the swimming speed and active metabolism within the range from 1.25 BL/s to 2.00 BL/s. Regarding this result, it was concluded that a part of the energy expenditure may be supplemented anaerobically in the range above 2.00 BL/s. We had already reported that levels of free fatty acid and glucose in serum in cultured red sea bream after exercising continuously over 4 h were significantly lower and higher in the range above 2.50 BL/s than in the range under 2.5 BL/s, respectively.[25] These findings support each other. However, the swimming speed at which the change from aerobic metabolism to anaerobic metabolism was recorded different between those results. This could be caused by it being trained swimming in the case of the latter.

Finally the annual change of active metabolism at the same swimming speed within the range from 1.25 BL/s to 2.00 BL/s showed a parallel pattern to that of field temperature (Fig. 4). Brett[16] also reported that active metabolism in sockeye salmon showed temperature dependence within the temperature from 5℃ to 15℃.

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養殖マダイにおける活動時代謝の年間環境水温サイクルに伴う変化

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養殖マダイにおける活動時エネルギー消費量の遊泳速度に伴う変化は，各月とも類似した漸増パターンを示した。しかし，その詳細な様相は遊泳速度の1.25BL/s以下と1.25～2.00，2.00以上や環境水温の向暖期と向寒期で異なった。そこで，エネルギー消費量と遊泳速度，環境水温の三者の間の関係を統計的に検討した。それらの結果に基づき，活動時エネルギー消費量の見積もりは，遊泳速度を1.25BL/s以上と以下および環境水温を向寒期と向暖期に4分別して求めた4式から算出が可能となった。