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Physiological response of scup, stenotomus chrysops, to a simulated trawl capture and escape event

Physiological Response of Scup, *Stenotomus chrysops*, to a Simulated Trawl Capture and Escape Event

PAPER

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ABSTRACT

*Scup (*Stenotomus chrysops*) were severely exercised by manual chasing for 6 min, and the clearance of lactate over a 12 hr period was evaluated. Lactate peaked from 0.5 to 1.0 hr following exercise with concentrations ranging from 61.0 to 126.0 mg/dL and returned to rested concentrations within 4 hr post-exercise. Concentrations of lactate in rested fish ranged from 5.2 to approximately 23.0 mg/dL. Fish were observed for 10 days following exercise for delayed mortality. A 100% survival of scup was observed with no significant difference between control and experimental populations.*

Swimming performance was evaluated for 14.0 to 15.0 cm fork length scup, with a towed stimulus through a still-water circular swimming channel, at prolonged and burst speeds. A maximum sustainable swimming speed of 2.2 BL/sec was observed. Between the speeds of 3.0 and 3.3 BL/sec and 4.4 BL/sec, endurance time significantly decreased with the increase in swimming speed. Blood lactate concentrations were measured at 0.5 and 4.0 hr post exercise, and were used as an indicator of white muscle recruitment. A significant difference was not found between rested and experimental mean lactate concentrations at the maximum sustainable swimming speed of 2.2 BL/sec. White muscle recruitment indicated by increases in lactic acid, was recorded at speeds above the maximum sustained swimming speed, and mean blood lactate concentrations were significantly different within blood sampling times and between swimming speeds.

Based on the results of our investigations of lactate recovery in scup following a simulated trawl capture and escape event, we believe that scup interacting with a bottom trawl and subsequently escaping, are physiologically stressed by the event, but recover in less than 6 hr. All experimentally treated fish survived both exhaustive exercise and prolonged swimming, suggesting encounter mortality is minimal. The results of this study do not address the effects of possible physical damage on escape or the effect of multiple encounters.

INTRODUCTION

Commercial trawl bycatch is defined as those non-target fishery resources which are retained within the cod-end, brought on board the fishing vessel and subsequently discarded. These fish are primarily juvenile and sub-adult stages of commercially important species (Howell and Langan, 1987), and experience high mortalities once discarded back to the sea (Dayton et al., 1995; and Kaiser and Spencer, 1995). Discard mortality is an important consideration in stock assessment analysis, since these fish are submitted to fishing pressure before they have recruited to the fishery based on landings. Other fish experience the trawl process, but escape. Some escapees avoid capture by the net utilizing burst or prolonged swimming speeds or behavioral responses which allow them to pass under, over or out of the path of the approaching net. Other escapees are swept into the body of the net due to swimming fatigue or failure of the optomotor response to the fishing gear, and are later able to escape through the open meshes in the cod-end portion of the net. These escaped fish, though not captured, may be physically damaged or physiologically stressed, so as to affect their survival. If these escaped fish subsequently die as a result of the interaction with the trawl then there is an encounter mortality associated with trawl fishing that must be quantified.

Scup (*Stenotamus chrysops*) is a hardy, fast swimming, demersal fish harvested by bottom trawls in the northwest Atlantic Ocean. Previous field studies have demonstrated a relatively high survival (100%) for scup that swim in codend of a trawl and escape after 18.0 min (DeAlteris and Riefsteck, 1993). Little is known about the physiological effects of sustained swimming leading to exhaustion that is associated with the trawl capture and escape process, although the physiology of swimming has been investigated (Rome et al., 1992a, 1992b), and provides a basis for the studies described herein.

Thus, the objectives of this study were to:

(1) characterize the generation and clearance of lactic acid in the blood of scup, and the potential delayed mortality following exhaustive exercise,
(2) establish the maximum sustained swimming speed of scup and endurance times at prolonged and burst swimming speeds; and
(3) evaluate the extent of anaerobic metabolism at prolonged and burst swimming speeds using blood lactate as an indicator.

The following swimming speed definitions are used in this study, as defined by Webb (1975). Intermediate swimming speeds are those

activity levels sustained for 200 min or more, the maximum of which being the maximum sustained swimming speed. Prolonged speeds are those with limited endurance from 15 sec to approaching 200 min. Burst swimming speeds are high activity levels maintained for less than 15 sec.

MATERIALS AND METHODS

Scup, *Stenatomus chrysops*, (10–20 cm) were obtained using traps from Narragansett Bay, Rhode Island, in late summer, acclimated to approximately 20 ± 1.0° C at 25 ± 1.0 ppt salinity, in an indoor recirculating salt water system, and held for a five month experimental period. Fish were exposed to an approximate 12:12 hr light/dark cycle. Feeding with fresh squid was suspended one week prior to each set of experiments, so as to avoid any effects of diet on the experiments.

Exhaustive Exercise Experiments

The exhaustive exercise experiments included four replicate trials, with sample sizes of 30, 8, 24, and 28 fish, respectively. In each trial severe exercise was imposed by transferring two fish into a circular 300 l tank filled with water from the same recirculating system as the holding tanks, and then chasing them vigorously with a blunt probe for six minutes. This was repeated as necessary for the total number of fish treated in the trial. Through preliminary exhaustive exercise experiments, 6 min was found to be the upper time limit that scup could continue short duration burst activities, being indicative of glycogen fueled white muscle contractions (Batty and Wardle, 1979; Wang et al., 1994). Therefore, in this study exhaustion is defined as: the condition at which the fish is no longer able to utilize glycolytic white muscle contractions to perform short duration burst swimming speeds. Temperature, salinity and dissolved oxygen readings were taken before and after each experimental trial, so as to document experimental conditions. Dissolved oxygen concentrations were maintained at approximately 95% saturation. Following exhaustion, fish were returned to holding tanks in water buckets which had been separated into chambers so that individuals could be identified and monitored for mortalities over the subsequent 12 hr. After the initial 12 hr period fish were transferred to holding tanks for an additional 10 days of monitoring. Past experience indicates almost all stress related mortalities in scup occur within 3 days of the stress event (DeAlteris and Reifsteck 1993). This period of time was assumed adequate to observe any mortalities initiated by opportunistic infection from stress-induced immunosuppression. During the 10 days of monitoring, a control group of 50 fish that had not been exhausted or had blood withdrawn were kept in a separate tank that was connected to the same recirculating system.

Whole blood samples (400 μl) were withdrawn using Tuberculin® 1 cc syringes with Precision Glide® 23GTW needles. Blood was withdrawn from an individual fish only once and then the fish was no longer used in the study. Both syringe and needle were heparinized using a solution of 0.05 g heparin (Sigma®) /8 ml distilled water. The withdrawal site was positioned mid-laterally between the dorsal and anal fins, just anterior to the caudal peduncle. Samples were taken at rest (control), immediately after exercise (t = 0), and at t = 0.5, 1.0, 2.0, 4.0, 8.0 and 12.0 hr following exhaustion with the following exceptions: Replicate 1 had no t = 0.5 hr sample and replicate 2 had no t = 12 hr sample.

Blood was immediately transferred to a heparinized 1.5 ml Epindorff® tube and centrifuged for 1.5 min at approximately 2,000 rpm, using a Fisher® Micro H microcentrifuge. Following centrifugation the blood plasma was examined for clarity and degree of hemolysis. Samples were classified as being clear, light tint, medium tint or darkly tinted. Samples possessing a high degree of hemolysis (dark red tint) were not used in the assay due to the possible contribution of lactate from ruptured red blood cells.

Sigma lactate reagent was prepared according to instructions. This reagent acts by converting lactic acid to pyruvate and peroxide. Peroxidase catalyzes the oxidative condensation of chromogen precursors to produce a colored dye with an absorption maximum at 540 nm (Sigma). Absorption values for lactate standard concentrations of 20, 80 and 120 mg/dL were used to construct calibration curves at the beginning of each experimental group. The absorption of the reagent was used as a blank versus the standard and test samples. From each individual fish plasma sample, three replicate assays were performed, so that a mean lactate value could be calculated. To each test sample 10μl of plasma was added and tubes were incubated for 5–10 minutes at room temperature (25–37° C). After incubation, the absorbence was measured using a Turner® model 340 spectrophotometer.

For Replicates 1–4 lactic acid concentrations were combined and the significance of differences of means ($P \leq 0.05$) with blood sampling intervals and between experimental replications were evaluated by an unbalanced design two-way ANOVA. On each experimental replicate the significance of differences of means ($P \leq 0.05$) within blood sampling intervals were tested and Duncan's Multiple Range Test was used to identify where the significant differ-

ences resided. Linear regression analysis and F-tests were performed on all time intervals to evaluate the relationship between length of time and the concentration of lactic acid in the blood.

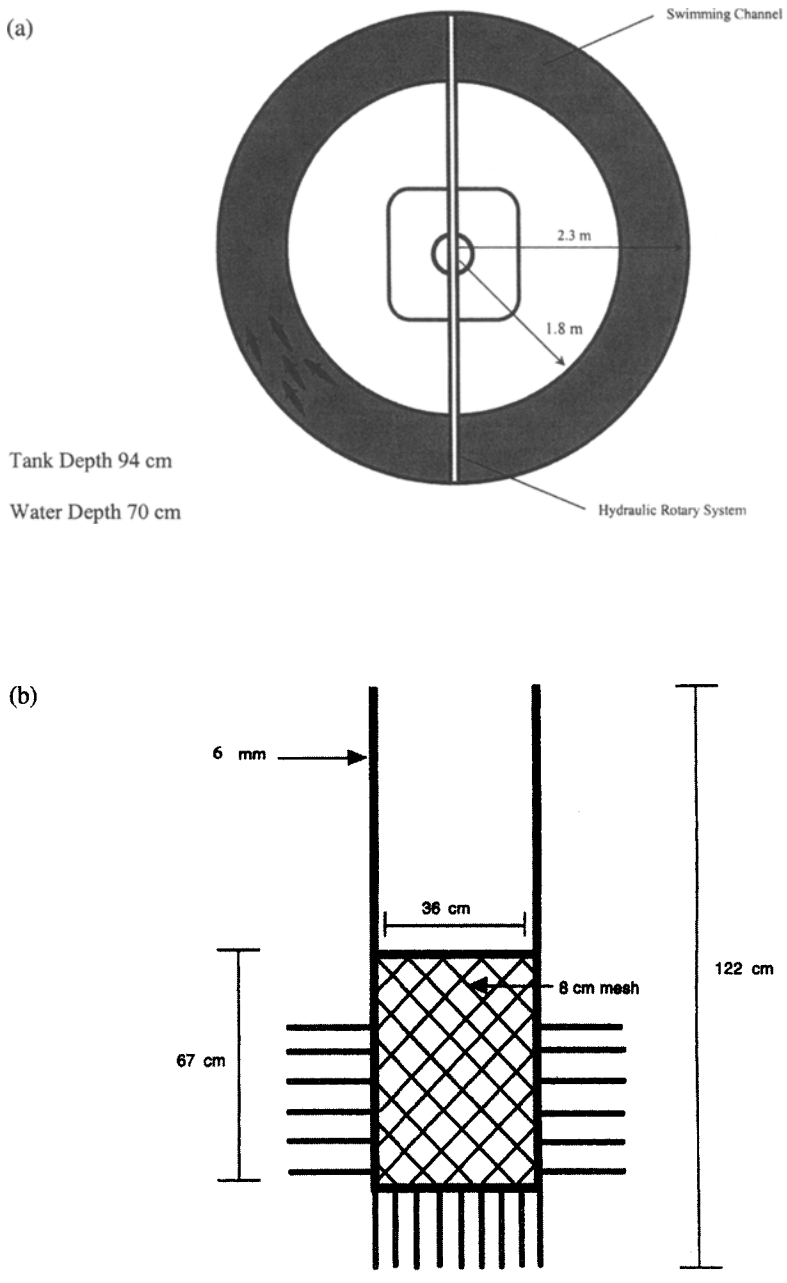
Swimming Performance Experiments

Swimming performance experiments were carried out in a fiberglass circular swimming channel. The outer and inner wall radii were 2.3 and 1.8 m respectively (Figure 1a) with a swimming channel 0.48 m in width. The tank height was 94 cm. However, for experimental trials the water depth was maintained at 70 cm. Before each experimental trial, 12 fish were moved using a bucket to a circular 300 l transfer tank filled with water from the same recirculating system (20.0 ± 1.0° C) as the holding tanks. Fish in this transfer tank were allowed to slowly equilibrate over a period of not less than 24 hr to water temperature of 12.0° C that existed in the experimental circular swimming channel. This change in water temperature and the required acclimatization is less than that experienced by scup in the natural environment as they migrate vertically in the summer stratified water column or horizontally along inshore/offshore thermal gradients.

A hydraulic powered rotary carriage system was designed to move a stimulus smoothly through the swimming channel at controlled speeds. The variable speed controller allowed speeds up to 200 cm/sec to be obtained, in reference to a 4.6 m outer wall diameter. The stimulus was a 67 × 36 cm rectangular frame made up of 6.0 mm steel bars (Figure 1b). Within the rectangular frame, 8 cm stretched mesh monofilament webbing was hung, to initiate a "herding" effect to drive the fish at predetermined swimming speeds. Standard 5.0 mm zip-ties were attached down the sides and bottom edge to further enhance the "herding" effect of the stimulus. During speed trials the stimulus was not observed to create substantial water disruption. The projected area of the "herding" stimulus was 4.0 % of the cross sectional area of the swimming channel, and water velocities produced by the carriage were used to adjust for true swimming speed.

Swimming speeds for each daily trial were chosen in order to establish the maximum sustained swimming speed (MSSS), and a range of endurance times at successively higher swimming speeds. Speeds were recorded in body lengths per second (BL/sec), given an average fish size of 14.4 cm (fork length). All swimming performance studies were conducted at 12.0° C in 25 ± 1.0 ppt salinity, and near 100% O_2 saturation was maintained. After acclimation, between 4–6 scup were randomly chosen from a population of 12 fish, and transferred to the swimming channel, with the exception of one trial and the MSSS experiment which used 12 individuals. Fish were allowed to adjust to the "herding" stimulus at low sustained swimming speeds (< 2.0 BL/sec) before the endurance trials began. The carriage speed was gradually increased to the target speed at which point the start time at this speed was noted and the trial began. When a fish was unable to continue at a given speed, thereby passing under or through the webbing of the stimulus, the time was noted as the endurance for that individual and the fish was removed from the swimming channel.

Figure 1. Design and specifications of: (a) circular swimming channel and carriage system, and (b) "herding" stimulus.



Maximum sustained swimming speed (MSSS) was defined as the maximum level of activity the fish was able to maintain for 200 min (Webb, 1975), after which point the endurance trial was ended. Two speed trials were performed at MSSS and four trials were conducted at each additional speed. Four swimming speeds were chosen for blood lactate analysis based on the initial endurance study results. The projected maximum sustained swimming speed of 2.2 BL/sec was chosen in addition to prolonged swimming speeds of 3.0 and 3.3 BL/sec, and a burst swimming speed of 4.4 BL/sec.

For each speed trial, eight scup were taken from the holding tank system in a similar fashion as described previously, and acclimated to the test temperature of 12° C. Six of these fish were used for each speed trial. Blood was withdrawn from two rested control fish and from three of the treated fish at 0.5 and 4 hr post-swimming, respectively. These times were chosen based upon results from the previous experiments where scup were exhaustively chased for 6 min and blood lactate accumulation and metabolization was monitored over a 12 hr period following exercise. The peak blood lactate accumulation occurred between 0.5 and 1 hr following severe exercise with a return to rested levels by 4 hr. Endurance lactate trials were pooled with previous swimming performance trials.

For all recorded swimming speeds, the endurance times for each trial within a speed were combined and the differences of means ($P \leq 0.05$) within experimental trials and between swimming speeds were evaluated using an unbalanced design two-way ANOVA. Endurance values were log transformed and plotted versus swimming speed. Linear regression analysis was performed to evaluate the relationship between swimming speed and endurance of scup.

Blood lactate concentrations at each sampling time were combined for each swimming speed and the differences of means ($P \leq 0.05$) within blood sampling time and between swimming speeds were also evaluated using an unbalanced design two-way ANOVA. For each swimming speed the differences of means ($P \leq 0.05$) with blood sampling intervals were tested and Duncan's Multiple Range Test was used to identify where the significant differences resided. Lactate concentrations as a function of sampling time were plotted to examine the trend of lactate accumulation with the observed swimming speeds.

RESULTS

Exhaustive Exercise Experiments

Six minutes of severe exercise failed to cause a delayed mortality in scup ($n = 120$) over the initial 12 hr monitoring period or during the following 10 days. However, the exhausted fish were observed to undergo pigmentation changes from a light blue green iridescence to a dark vertically banded configuration.

The two-way ANOVA revealed that significant interaction existed between blood sampling time and experimental replicate ($P < 0.0003$). Significant differences within blood sampling time means ($P < 0.0001$), and between experimental replicate means ($P < 0.0012$) were also observed. As a result of the significant difference between experimental replicates, data for the four replicates were not combined. Common to all replications, blood lactate rose rapidly and peaked after the first 0.5 hr, then significantly decreased by 4.0 hr and continued to show decreased concentrations at the 8.0 and 12.0 hr sampling intervals (Figure 2). The largest degree of variation within the sampling times are observed during the period of most active production and clearance of lactic acid, those being $t = 0$, 0.5, 1.0 and 2.0 hr. Mean and standard error of the mean values (S.E.M.) for the four replications, over the 12 hr of sampling are listed in Table 1. Duncan's Multiple Range Test indicated a return to the control lactate concentrations at 4 hr post exercise for replications 1, 2, and 4. Experimental replicate 3 returned to the control concentrations at the 8.0 hr sampling time. Control concentrations ranged from approximately 5.2 to 22.9 mg/dL lactate. Peak lactate concentrations ranged from approximately 61.0 to 126.3 mg/dL between 0 and 1.0 hr post exercise.

Fish size was not found to significantly effect lactate concentration for all blood sampling intervals with the exception of control ($P < 0.0227$) and 0.5 hr ($P < 0.0005$) following exercise (Table 2). In the control samples, lactate concentration decreased with increasing fish size from 11 to 20 cm; and in the 0.5 hr samples lactate concentrate increased with increasing fish sizes from 11 to 14 cm. The R^2 values for these two groups were 0.339 and 0.614, respectively.

Swimming Performance Experiments

During normal room-light conditions and with the "herding" stimulus standing still, most scup remained as a school, but were motionless at mid to bottom water tank depths. At times scup were observed to swim at low speeds around the swimming channel but not in a continuous fashion. Initial introduction of the stimulus would cause a brief increase in swimming speed away from the carriage stimulus system. Once accustomed to the stimulus, fish would remain within approximately four body lengths of the stimulus swimming in a smooth continuous manner. At increased performance

levels different swimming strategies were observed. During swimming trials fish did not incur any pigmentational changes associated with stress which were observed in the exhaustive exercise experiments. This does not rule out any stress caused by the "herding" stimulus, however it does suggest that the stimulus did not create unusual swimming behavior that may have biased the results.

A MSSS of 2.2 BL/sec was recorded for the 14.4 cm (average fork length) scup at 12 °C. All 20 individuals tested were still swimming steadily after 200 min, at which point the trials were ended (Webb, 1975). At speeds of 3.0, 3.3 and 4.4 BL/sec various endurance times were recorded (Table 3). The relationship between swimming speed (U, in BL/sec) and endurance time (E, in log(sec)), as estimated by linear least squares regression (Figure 3) is: log E = 5.9191 − 0.96233 U with R^2 = 0.972.

The two-way ANOVA revealed a significant difference within mean endurance time for the three experimental swimming speeds ($P < 0.0001$), but not between swimming trials for a given speed. Given that no significant difference was found between swimming speed trial means, all trials for a given swimming speed were combined.

The patterns of lactate concentration accumulation and clearance for all speeds is similar to that observed in the exhaustive exercise experiments (Figure 4). The mean and standard error of the mean (S.E.M.) levels of blood lactate at control, 0.5 and 4.0 hr sampling times for the three swimming speeds, as well as Duncan's Multiple Range Test results are listed in Table 4. At the MSSS of 2.2 BL/sec, Duncan's Test revealed that there was no significant difference between control or rested concentrations of blood lactate means, and post-exercise levels. At the prolonged swimming speed of 3.0 BL/sec the same test revealed a significant difference in lactate means ($P < 0.0012$) for the blood sampling times. Blood lactate significantly increased from rested concentrations at 0.5 hr post-exercise averaging 45.7 mg/dL lactate, then significantly decreased to 26.6 mg/dL at 4.0 hr following the endurance trials. However, mean lactate concentrations did not return to rested concentrations within the observation period. At the burst swimming speed of 4.4 BL/sec, the Duncan's test revealed a significant difference in mean lactate concentration ($P < 0.0156$) for blood sampling times. Lactate significantly increased from rested concentrations at the 0.5 hr sampling interval, with an average lactate concentration of 26.5 mg/dL. Concentrations then significantly decreased returning to control levels at 4.0 hr following the endurance trials. It is also interesting to note that the maximum lactate concentration was observed at the prolonged swimming speed of 3.0 BL/sec, not the burst swimming speed of 4.4 BL/sec, this suggests that prolonged swimming may be more exhaustive than burst swimming.

Mean blood lactate concentrations were found to be significantly different within sampling time ($P < 0.0001$) and between swimming speeds ($P < 0.0001$). Also, a significant effect for blood sampling time and swimming speed interaction was also observed ($P < 0.0059$).

Figure 2. Mean lactate accumulation and clearance over 12 hr following exhaustive exercise, for Experimental Replicates 1–4. Error bars indicate standard error of the mean (S.E.M.). Asterisk (*), symbols + and ^ indicate significant differences from one another and from non-symbol points, respectively.

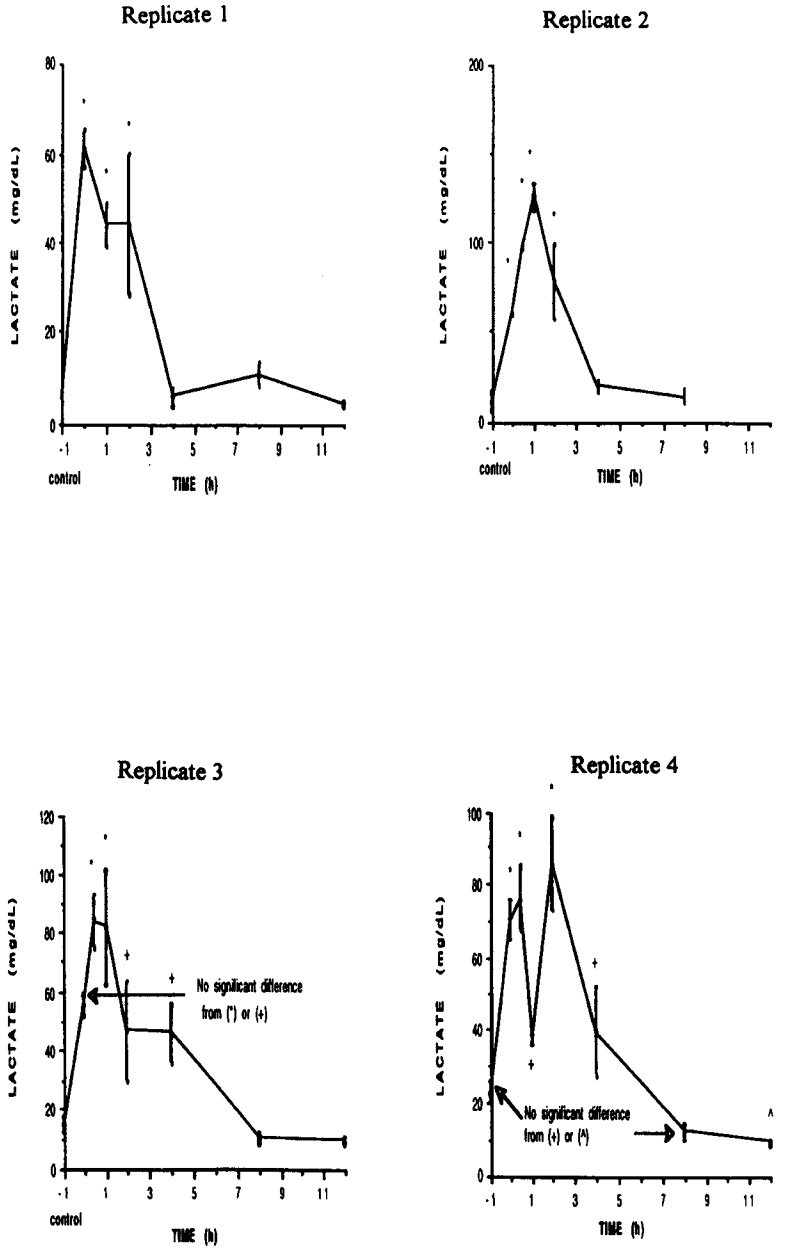


Table 1. Mean lactate concentrations (mg/dL), standard error (S.E.M.) values, results of Duncan's Multiple Range Test, sample size for replicates 1 (df=30), 2 (df=8), 3 (df=24) and 4 (df=28).

Replicate	Sampling Time (hr)	Mean (mg/dL)	S.E.M.	Duncan Grouping	Sample Size
1	control	5.19	1.11	B	6
	0	60.99	4.03	A	5
	0.5	*	*	*	*
	1	44.13	4.66	A	4
	2	43.92	16.13	A	5
	4	6.11	1.70	B	4
	8	10.63	2.40	B	5
	12	4.53	0.56	B	8
2	control	11.02	5.40	B	2
	0	59.14	0.00	A,B	1
	0.5	97.23	1.51	A,B	1
	1	126.26	6.94	A	2
	2	77.36	21.79	A,B	4
	4	19.04	2.33	B	2
	8	12.97	3.40	B	2
	12	*	*	*	*
3	control	15.01	2.19	C	4
	0	55.70	3.76	A,B	4
	0.5	84.03	8.96	A	4
	1	81.83	18.83	A	4
	2	46.44	16.67	B	3
	4	45.95	9.91	B	5
	8	10.28	1.45	C	4
	12	9.52	1.05	C	4
4	control	22.85	2.88	B,C	3
	0	70.82	5.34	A	5
	0.5	76.32	8.76	A	9
	1	38.77	2.33	B	5
	2	85.93	12.91	A	3
	4	39.76	12.44	B	4
	8	12.24	2.30	B,C	4
	12	8.89	0.90	C	3

Table 2. Results of linear regression analysis of lactate concentrations as a function length of fish, and F-test results ($\alpha = 0.05$). Asterisk (*) indicates statistical significance.

Control sampling interval:	$y = 35.547 - 1.5867X$	$(R^2 = 0.339)^*$
T=0 sampling interval:	$y = 84.285 - 1.6004X$	$(R^2 = 0.114)$
T=0.5 hr sampling interval:	$y = 224.02 + 24.221X$	$(R^2 = 0.614)^*$
T=1.0 hr sampling interval:	$y = 36.746 + 7.5638X$	$(R^2 = 0.230)$
T=2.0 hr sampling interval:	$y = 9.7323 + 3.8148X$	$(R^2 = 0.062)$
T=4.0 hr sampling interval:	$y = 10.345 + 2.8473X$	$(R^2 = 0.109)$
T=8.0 hr sampling interval:	$y = 2.6177 + 0.66623X$	$(R^2 = 0.069)$
T=12.0 hr sampling interval:	$y = 1.9243 + 0.33562X$	$(R^2 = 0.135)$

DISCUSSION

Exhaustive Exercise Experiments

Severe exercise did not result in an immediate mortality over the initial 12 hr of monitoring or during the 10 days of post-exercise observation. In addition to the 6 min of forced exhaustive exercise these fish suffered a removal of 400 µl of blood and air exposure ranging from 30 sec to approximately 1 min. Also, there were no observed mortalities within the control group of animals. Research by DeAlteris and Reifsteck (1993) and Williams (1995) also substantiate the "hardiness" of this species. Williams (1995) analyzed the survival of scup after recreational catch and release. He concluded that handling time and jaw hooking locations had no effect on mortality, while more destructive hooking locations such as the gill and esophagus resulted in 95.9% mortality. The results of an angler survey calculated an overall mortality for scup of only 4.0%. DeAlteris and Reifsteck (1993) used a towed codend simulation apparatus (TCESA) to investigate escapement behavior and survival of scup from the codend of a demersal trawl. They concluded the survival of codend escapees was excellent, with no significant differences observed between control and square- and diamond-mesh-treated fish. DeAlteris and Reifsteck (1993) as well as the results of the present study support the conclusion that the capture process of the mobile fishing gear does not appear to cause a physiologically induced delayed mortality created by anaerobic metabolism, or through the process of cod-end escapement. However, these studies do not address survival probability after compacting and physical damage resulting from commercial scale demersal trawling or increased predation of exhausted fish escaping from the trawl net.

During the periods of manual chasing, scup were observed to undergo pigmentation changes from their usual light blue green iridescence to a dark vertically banded configuration. The banded pattern lasted for a period up to six hours, which may be associated with a stress response to the manual chasing in this case. However, the same banding pattern was observed each morning following 12 hours of dark, and during times of aggression between fish while feeding. Similar responses to stress are seen in many fishes (Zimmerer and Kallman, 1988). The pigmentation change from light to dark would be more advantageous to a fish which tends to be low in the water column such as scup, which feed on crustaceans and marine worms found on the bottom substrates (Bigelow and Schroeder, 1953), than more pelagic organisms which tend to become lighter and more silvery when disturbed (Baerends and Baerends-Van Roon, 1950). These physiological color changes occur rapidly through direct neural input, appear to be pre-set patterns and may act through catecholamines. The dark banding seen in scup may result from epinephrine released by chromaffin cells which act on b-adrenoreceptors on chromatophores causing a rapid darkening.

The physiological changes occurring during recovery from severe exercise in surviving fish have been previously studied (Batty and

Figure 3. Swimming speed (BL/sec) and endurance (log sec) of scup. The predicted line results from the least squares regression and is described by: logE = 5.9191 − 0.96233 U (R^2 = 0.972).

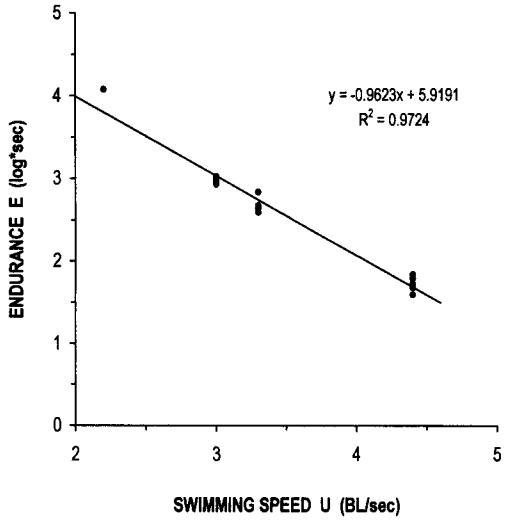
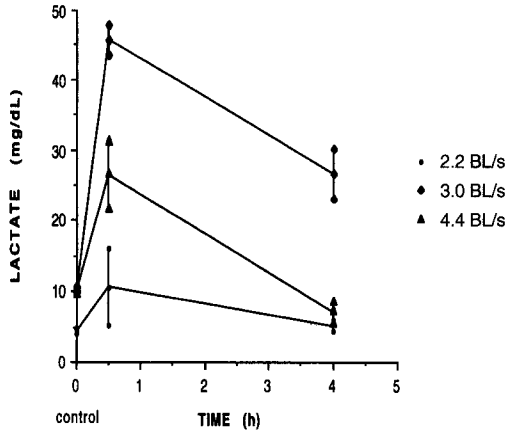


Figure 4. Mean lactate concentrations for 2.2, 3.0 and 4.4 BL/sec endurance trials at control 0.0, 0.5 and 4.0 hr. Error bars indicate standard error of the mean (S.E.M.)



Wardle, 1979; Milligan and Wood, 1987; Schwalme and Mackay, 1991; Young and Cech, 1993; Tang et. al., 1994). The observed post-exercise acidosis is initially due to both a substantial respiratory acidosis and a release of metabolic protons into the blood from the white muscle. Wood et al. (1983) observed in trout that at 0.5 hr post-exercise the acidosis was almost entirely metabolic. During the periods of burst activity the white muscle mass had built up massive concentrations of lactate and equimolar levels of protons. They concluded that the release and metabolism of lactate and protons from the muscle appeared to be separate events. Net proton movement is inhibited by the acidic blood pH resulting from the exhaustive exercise, which prevents a possibly fatal blood acidosis.

Table 3. Mean endurance time (sec), standard error (S.E.M.) values and sample sizes (n) for swimming speeds of 3.0, 3.3, 4.4 BL/sec.

Speed (BL/sec)	Trial	Mean (sec)	S.E.M.	Sample Size
3.0	1	907.0	104.3	4
	2	852.5	206.5	4
	3	958.0	204.4	4
	4	1065.8	27.4	6
	5	1001.8	80.1	5
3.3	1	474.3	74.3	4
	2	92.3	63.9	4
	3	441.3	46.6	4
	4	689.58	22.0	12
4.4	1	69.3	9.3	4
	2	47.5	3.8	4
	3	62.0	12.8	4
	4	53.3	2.6	6
	5	39.2	3.4	6

Table 4. Mean lactate concentrations (mg/dL) standard error (S.E.M.) values, results of Duncan's Multiple Range Test ($\alpha = 0.05$), and sample sizes (n) for swimming speeds of 2.2, 3.0, and 4.4 BL/sec.

Speed (BL/sec)	Time hr	Mean (mg/dL)	S.E.M.	Duncan Grouping	Sample Size
2.2	control	4.52	0.38	A	2
	0.5	10.65	5.37	A	3
	4.0	5.96	1.71	A	3
3.0	control	10.19	0.45	A	2
	0.5	45.70	2.25	B	3
	4.0	26.64	3.52	C	3
4.4	control	10.19	0.45	B	2
	0.5	26.50	4.71	A	3
	4.0	7.24	1.40	B	3

However, the efflux of lactate continues, and up to a two-fold increase in lactate was observed in trout at 2 hr post-activity, with a return to rested values after 8 hr. Scup followed a similar trend, between 0.5 and 1.0 hr after exertion lactate concentrations were at highest levels reaching concentrations as high as 126 mg/dL whole blood lactate. In contrast scup blood lactate returned to control concentrations within 4 hr following exercise.

The rapid metabolism of lactate from the white muscle mass has not been explained satisfactorily. It is generally accepted that lactate is released from the muscle tissue, converted to pyruvate where it undergoes gluconeogenesis within the liver, and converted back to glucose where it can be stored within the muscle tissue as glycogen. Studies by Wood et al. (1983), Keiffer et al. (1994), and Wang et al. (1994) suggest that the major fate of lactic acid is not its efflux into the blood, but that the majority remains within the white muscle tissue where it is metabolized. Buck et al. (1992) indicate that if hepatic gluconeogenesis is the major route of lactate removal post-exercise in the

skipjack tuna, it would require up to 3800 hr. Metabolic pathways have been suggested to be in *vivo* gluconeogenesis and lactate oxidation. However, if lactate oxidation does occur, it is a slow reaction which would not account for the observed rapid metabolization, and there has been no explanation as to how glycogenesis would occur.

Future research on metabolic recovery following exhaustive exercise should include more extensive studies evaluating the proposed glycogen-lactate-glycogen cycle in the white muscle of fish. Many hypotheses have been proposed as to the cause of fatigue induced mortality such as muscle tissue necrosis, severe blood acidosis and cortisol-induced immunosuppression. Studies have been performed on recreationally important species evaluating the effects of angler stress on these stocks (Ferguson et al., 1992; Gustaveson and Wydoski, 1991; and Williams, 1995). Given the present over-fished condition of most commercially important stocks (Anonymous, 1995), a more complete understanding of the physiological effects caused by the capture process of mobile fishing gears would be useful. This would aid fisheries scientists in estimating the encounter mortality associated with fish interacting but not being captured by the trawl gear.

Swimming Performance Experiments

Scup (14–15 cm) achieved a MSSS of 2.2 BL/sec or 31.0 cm/sec at 12° C. As swimming speed increased above the MSSS endurance was reduced. Endurance averages fell from approximately 950 to 500 sec at speeds of 3.0 and 3.3 BL/sec, respectively, and fish were only able to maintain burst speeds of 4.4 BL/sec for approximately 50 sec. Similar results have been observed for other bony fishes, although the maximum speed and endurance over prolonged and burst speeds are variable (He and Wardle, 1988; He, 1991; Mesa and Olson, 1993). Variability is due largely to particular body designs, environments and ratios of the muscle fiber types. The propulsion systems of fish can be separated into two categories, those being median and paired fin (MPF) and body and caudal fin (BCF) propulsive mechanisms (Webb, 1975; Evans, 1993). Most fish will utilize both forms of propulsion depending on their behavior. MPF propulsion is generally used during slower motion and fine maneuvering, whereas BCF propulsion is used during cruising, feeding, fright and escape behaviors. High performance fast swimming fish are usually fusiform in shape with an increased body depth, have a low number of short amplitudinal half-waves during the swimming movement, and possess a stiff caudal peduncle with a large tail for efficient transmission of force to the water. High performance fish such as mackerel, tuna or billfish are however unable to perform the high degree of maneuverability and wide range of movements seen in MPF propulsive fish such as reef fish. Scup fall between the two, possessing a slender fusiform and deep body design with a forked caudal fin and narrow caudal peduncle (Bigelow and Schroeder, 1953). Scup utilize a carangiform mode of swimming characterized by their body and caudal fin usually being thrown into a wave, with up to one half-wavelength within the length of the body. The amplitude of the half-wave typically increases over the posterior third of the body length (Webb, 1975). Scup are however, able to undergo fine movements utilizing their well developed median and paired fins for feeding on crustaceans and sand worms found on the ocean floor (Bigelow and Schroeder, 1953).

Once above the MSSS, fatigue results from the incorporation anaerobic white muscle fibers and muscle glycogen depletion (Rome et al., 1992a, 1992b; Nielsen et al., 1994). At the MSSS of 2.2 BL/sec there was not a significant change in lactate concentrations from rested and speed trialed fish. At 3.0 BL/sec a rise in blood lactate was observed 0.5 hr following the endurance trial from rested concentrations. After 4.0 hr lactate concentrations had not returned to rested concentrations, although they were significantly decreased from the 0.5 hr sampling interval. At the burst speed of 4.4 BL/sec, a rise in lactate concentration from control was observed with a return to rested concentrations by 4.0 hr following the endurance trial. The peak in lactate concentration seen at 0.5 hr was not as high as that observed for 3.0 BL/sec at the same sampling time. This results from a shorter duration of the swimming activity therefore, a diminished anaerobic phase. It is not believed that the 4.4 BL/sec trials were representative of "true" endurance trials. The high end of burst activities for scup was 4.4 BL/sec. At the beginning of the speed trials, fish elicited erratic burst and coast behaviors maintaining great distances from the carriage. This response was short in duration (generally < 1.0 min), at which point individuals would immediately cease swimming and allow the stimulus to pass over them.

Generally swimming performance studies are carried out in round tanks, using circulating water flume systems or within still water channels (Wood et al., 1983; He and Wardle, 1988; Wardle et al., 1989; Barbin and Krueger, 1994). Weihs (1981) concluded that fish swimming in a circular cruising channel were physiologically compromised when compared to fish swimming freely in a straight line. The disadvantage originates from the added stress produced by the centripetal force required for continued motion in a curved path, and results in an

increased metabolic rate caused by the circular swimming channel. Based on these studies, the correction ratio for swimming speed when swimming in a straight track (U_s) to that in a curved track (U_c), expressed as Us/UC, for scup in these experiments was estimated to be 1.064. Therefore scup would have swum 6.4% faster on a straight track, which would increase the observed MSSS from 2.2 to 2.3 BL/sec with the same available swimming power. Similar results were found by He and Wardle (1988) for mackerel, herring and saithe. Estimated increases ranged from 5% for mackerel to 10% faster for a 50.0 cm saithe. The larger the fish and the smaller the radius of the annular tank, the greater the effect of path curvature on the swimming performance of the test species.

Generally, commercial scup trawling speeds range from 130 to 154 cm/sec (2.5 to 3.0 knots). Based on the average fish size in this study of 14.4 cm, scup would have to maintain speeds of 9.0 to 11.0 BL/sec to escape from the mouth of a bottom trawl. Given the corrected MSSS of 2.3 BL/sec and only an observed average endurance of 50 sec at 4.4 BL/sec, it is unlikely that scup of this size would swim for an extended period in front of or within the net before tiring and being susceptible to size selectivity of the cod-end meshes of the gear. DeAlteris and Reifsteck (1993) observed near 100.0% survival of scup following escapement from the codend of a demersal trawl; however they reported mean swimming times up to 18.0 min for juvenile scup within a towed cod-end at 128.0 cm/s. This is well beyond the prolonged or burst swimming capabilities of scup. This provides a compelling illustration of the effect of water entrainment and boundary layers created within the cod-end. It would be of great interest to experimentally determine if the fish are actually swimming, and if so at what relative speed to water inside the net, or is most of their energy being used to maintain position and balance? Future research should include more underwater documentation of fish-gear interactions so that fish behaviors may be used to decrease juvenile catches. In addition, characterization of swimming capabilities of a greater range of commercially important species should be addressed, as well as documentation of the stress induced from maintaining these speeds.

SUMMARY AND CONCLUSIONS

Scup were severely exercised by manual chasing for 6 min, and the clearance of lactate over a 12 hr period was evaluated. Rested concentrations of lactate ranged from 5.2 to approximately 23.0 mg/dL. Lactate peaked from 0.5 to 1.0 hr following exercise with concentrations ranging from 61.0 to 126.0 mg/dL and returned to rested concentrations within 4 hr post-exercise. Fish were observed for 10 days following exercise for delayed mortality. A 100% survival of scup was observed with no significant difference between control and experimental populations.

Swimming performance was evaluated for 14.0 to 15.0 cm fork length scup, with a towed stimulus through a still-water circular swimming channel, at prolonged and burst speeds. A maximum sustainable swimming speed of 2.2 BL/sec was observed. At speeds of 3.0, 3.3 and 4.4 BL/sec, endurance time significantly decreased with the increase in swimming speed. Blood lactate concentrations were measured at 0.5 and 4.0 hr post exercise, and were used as an indicator of white muscle recruitment. A significant difference was not found between rested and experimental mean lactate concentrations at the maximum sustainable swimming speed of 2.2 BL/sec. White muscle recruitment indicated by increases in lactic acid, was recorded at speeds above the maximum sustained swimming speed, and mean blood lactate concentrations were significantly different within blood sampling times and between swimming speeds.

The results of our investigations suggest that scup interacting with a bottom trawl and subsequently escaping, are physiologically stressed by the event, but recover pre-exercised levels of plasma lactate in less than 6 hr. All experimentally treated fish survived both exhaustive exercise and prolonged swimming, suggesting encounter mortality is minimal. The results of this study do not address the effects of possible physical damage on escape or the effect of multiple encounters.

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