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Temperature magnified postcapture mortality in adult sablefish after simulated trawling

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For sablefish *Anoplopoma fimbria* that had been transferred abruptly from ambient (5–7°C) to temperatures ranging from 15 to 20°C for 30 min followed by 15 min in air (19.5°C), mortality increased with temperature. Mortality occurred at lower temperatures for sablefish that were net-towed for 4 h at ambient temperature before exposure to a rapid increase in temperature. A clear relationship was apparent between serum lactate and temperature with lactate increasing as temperature increased. For treatments in which mortality did not occur, lactate decreased sharply within 24 h, suggesting recovery. It would appear that the critical postcapture temperature for sablefish that reside and are captured at 4–6°C, would be between 12 and 15°C. The results of this study suggest that fishery management strategies designed to increase postcapture survival of sablefish bycatch should include a consideration of the impact of exposure to seasonal thermoclines and seasonally elevated air temperatures.

Key words: by-catch; physiology; survival; stress.

INTRODUCTION

The ultimate fate of fish that survive capture and are returned to the sea as by-catch is largely unknown. Depending on the gear type and fishing method, the more obvious inducers of capture stress include net entrapment, mesh passage, crushing and wounding, sustained swimming until exhaustion, changes in pressure, hooking and exposure to air (Fernö, 1993; Chopin & Arimoto, 1995; Olla *et al.*, 1997). One major impediment to being able to predict accurately whether fish will survive after capture is the dearth of knowledge of how certain key environmental factors might interact to magnify the stress that is induced by the capture process. Temperature is one of several key environmental factors that could interact with fishing-induced stressors to affect survival. Temperature controls virtually all physiological functions and plays a major role in the life history of all species by exerting a critical influence on growth, metabolism, reproduction, distribution, behaviour and, ultimately, survival (Brett, 1970; Fry, 1971).

Based on the habitat in which a fish species resides, the temperatures at which it is caught and acclimated may be quite different from those that it would be subsequently subjected to during gear retrieval. A rapid increase in temperature

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can induce mortality directly or reduce indirectly the potential for survival by diminishing the capability to deal with basic ecological challenges such as food acquisition and predator avoidance (for reviews of how stress may effect behaviour, see Olla *et al.*, 1980; Schreck *et al.*, 1997). When added to the stress induced by capture, temperature could exert a potent influence on survival.

Off the north-west coast of the U.S.A., demersal fish species caught below 100 m during summer and early autumn often are exposed to rapid changes in temperature as they are brought towards the surface through the sharp thermocline that typifies the thermal regime of the fishing grounds. During this time of year in the waters off of Oregon and California, the temperature change from bottom to surface can range from 6 to 17° C (Tully, 1964; Huyer, 1977; Hunter *et al.*, 1989); during years when an El Niño is present, e.g. 1982–1983, 1997; temperature differences could be even greater (Huyer & Smith, 1985; Smith, pers. comm.). Captured fish also face the additional stress imposed by elevated deck temperatures.

While there is a plethora of information on the effects of temperature on a number of fish species (e.g. Fry, 1967; Brett, 1970; Olla *et al.*, 1985) little is known about how this factor may interact with capture stressors. Sablefish *Anoplopoma fimbria* Pallas is a highly valued species that is the subject of an intense commercial fishery off the Pacific Coast of North America. Fish may be caught by trawl, longline or trap typically at depths ranging from 155 to 1350 m (Hunter *et al.*, 1989; Macewicz & Hunter, 1994). When not targeted for capture, they are often caught as bycatch in other directed groundfish fisheries. At least during summer and early autumn, there is a high probability that sablefish during capture would be subjected to sharp differences in temperature that could induce acute levels of stress.

Sablefish have a high propensity for recovery from stress induced by simulated trawling and air exposure in the absence of any thermal challenges (Olla *et al.*, 1997). Our aim in this study was to use these previous findings as a basis for examining under controlled laboratory conditions, how rapid exposure to elevated temperatures would influence recovery from the effects of simulated trawling and air exposure. The temperature changes that were imposed matched those which adult sablefish might face under natural harvest conditions. Additionally, we employed a suite of biochemical measures that could act as surrogates to estimate recovery and mortality. The measurement of stressor-induced departures from established biochemical norms in fish has been shown to be a sensitive and pertinent tool for assessing the effects of stress and predicting mortality (Schreck, 1990; Schreck *et al.*, 1997).

MATERIALS AND METHODS

Adult sablefish (40–50 cm L_F) were collected in traps offshore from Newport, Oregon and held in the laboratory for 6–12 months prior to testing. Fish were reared in circular tanks (4.5 m diameter, 1.0 m depth; 15 904 l volume) supplied with flow-through sea water (20 l min⁻¹; 4–6° C, 30–32‰ salinity, O₂ >90% saturation) and fed to satiation on whole dead squid twice a week. Fish used in experiments ranged from 52 to 70 cm L_F .

The time course of elevation of body core temperature was determined by transferring sablefish from rearing temperature ($5.8 \pm 0.1^\circ\text{C}$; mean \pm 1 s.e.) to a tank (3.0 m diameter, 1.0 m depth; 7068 l volume) containing heated sea water ($16.0 \pm 0.0^\circ\text{C}$). Replicate

fish ($n=8$) were immobilized in a nylon mesh (1.0 cm) bag (1.0 m long \times 0.7 m wide) and temperature was sampled electronically every 5 min for 30 min by insertion of a muscle probe. The muscle probe was a stainless steel penetration thermocouple probe (1.6 mm diameter), inserted 30 mm into the central dorsal area of the fish and sampled using a standard thermocouple thermometer. The probe and thermometer were calibrated using an NIST standard thermometer.

The effects of elevated temperature and exposure to air on mortality were determined by transferring fish from rearing tanks ($5.7 \pm 0.2^\circ\text{C}$) to a tank with elevated sea water temperature and subjected to 15.0 ± 0.0 , 17.0 ± 0.0 , 18.0 ± 0.0 or $20.0 \pm 0.0^\circ\text{C}$ for 30 min while in a nylon mesh bag, followed by 15 min in the air ($19.5 \pm 0.5^\circ\text{C}$). After treatment, replicate ($n=6$) fish were placed in recovery tanks (4.5 m diameter, 1 m depth) supplied with flow-through sea water (10 l min^{-1} ; $4\text{--}6^\circ\text{C}$, 30–32‰ salinity, $\text{O}_2 > 90\%$ saturation) and divided in quarters by clear acrylic partitions to form four sections. One fish was placed in each section; either transferred from a rearing tank (untreated baseline) or after having been exposed to warm water and air. Mortality was noted as it occurred.

Towing stress was imposed by using a modification of a towing apparatus previously described in Olla *et al.* (1997). In brief, the apparatus had two nets suspended at the ends of two rotating arms in a tank (4.5 m diameter, 1 m depth) to simulate cod-ends of fishing trawls. The nets were cylindrical (1.2 m length, 0.7 m diameter) and constructed with 2.5 cm nylon diamond mesh. Nets were towed in lighted conditions ($1.0\ \mu\text{mol photons m}^{-2}\text{ s}^{-1}$) at 1.1 m s^{-1} , a speed at which sablefish could not swim. While the dimensions of the towing arm and apparatus were similar to the first version, the apparatus was strengthened and the size of the motor increased from 0.5 to 5 hp.

The combined effect of towing and temperature on mortality was determined using fish that had been towed for 4 h ($4.8 \pm 0.2^\circ\text{C}$), and then subjected to either 4.3 ± 0.2 , 12.0 ± 0.0 , 15.0 ± 0.0 or $16.0 \pm 0.0^\circ\text{C}$ sea water for 30 min while placed in a nylon mesh bag, followed by 15 min in the air ($18.3 \pm 0.3^\circ\text{C}$). Towing simulated capture at depth, while exposure to elevated sea water temperature simulated net passage through a thermocline and exposure to the air simulated time on the deck of a fishing vessel. Treated replicate ($n=8$) fish were placed in recovery tanks (4.5 m diameter, 1 m depth) supplied with flow-through sea water (10 l min^{-1} ; $4\text{--}6^\circ\text{C}$, 30–32‰ salinity, $\text{O}_2 > 90\%$ saturation) and divided in quarters by clear acrylic partitions to form four sections. One fish was placed in each section; either that had been towed, held at 4.3°C and in the air (towed cold control), or that had been towed, held at 12.0 , 15.0 or 16.0°C and in the air (towed heated treatment). Mortality was noted as it occurred.

Treatments of sablefish for determining the effects of towing and temperature together were repeated and fish were killed with 400 ppm MS-222 immediately after air treatment. Blood was sampled from the caudal vein of fish into heparinized capillary tubes; the plasma was separated from other constituents by centrifugation for 3 min at 2500 g. Plasma was collected and frozen at -80°C until analysis for cortisol, glucose and lactate. Cortisol concentrations were determined in $10\ \mu\text{l}$ of plasma by radio-immunoassay techniques as described and originally validated by Redding *et al.* (1984) and validated for sablefish by Olla *et al.* (1997). Glucose was determined using standard colorimetric methods (Wedemeyer & Yasutake, 1977). Lactate was determined using standard colorimetric methods (Passonneau, 1974).

Confidence intervals (95% CI) for per cent mortality were estimated using the method of Conover (1980). Standard one-way analysis of variance (ANOVA) procedures using Statistix analytical software (Version 1.0 for Windows) were used for analysis of physiological data.

RESULTS

When sablefish that were acclimated to 5.8°C were transferred abruptly to 16.0°C , body core temperature rose to $12.8 \pm 0.3^\circ\text{C}$ ($n=8$; mean \pm 1 s.e.) after 15 min, an increase of 121% (Fig. 1). By 30 min body core temperature had reached $15.6 \pm 0.1^\circ\text{C}$.

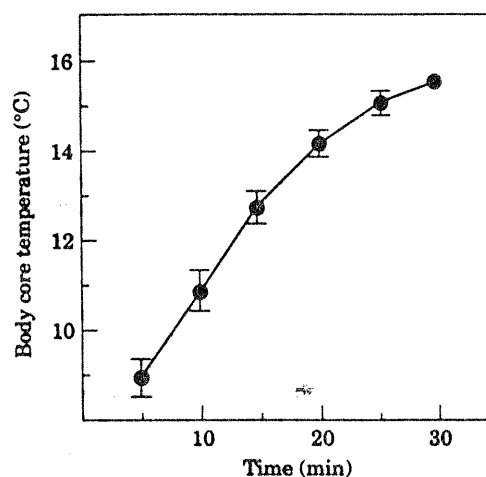


FIG. 1. Time course of body core temperature in sablefish acclimated initially to 5.8° C and transferred abruptly to 16° C. Values are mean \pm 1 s.e. ($n=8$) and confidence intervals are included in points when not indicated.

When sablefish that were acclimated to 5.7° C were transferred abruptly to a water temperature of 15.0° C for 30 min and then held in air for 15 min (19.5° C), all fish survived ($n=6$) for at least 60 days [Fig. 2(a)]. However, abrupt transfers of fish to temperatures that exceeded 15.0° C caused a concomitant rise in mortality within 48 h. A transfer from 5.7° to 17.0° C caused mortality to increase to 33% ($n=6$; 95% CI=3–77%); at 18° C, mortality more than doubled to 83% ($n=6$; 95% CI=35–100%); at 20° C mortality reached 100% ($n=6$). All fish that had survived after 48 h were still alive after 60 days.

Sablefish that were net towed for 4 h at 4.8° C, held for 30 min at either 4.3° or 12.0° C and then exposed to air for 15 min (18.3° C), suffered no mortality after 48 h ($n=8$) [Fig. 2(b)] and in fact were still alive after 60 days. But when the water temperature the fish were exposed to for 30 min between net towing and air exposure was raised to 15° C, mortality after 48 h was 38% ($n=8$, 95% CI=12–75%). Raising temperature to 16.0° C caused mortality to double to 75% ($n=8$; 95% CI=35–98%) in 48 h. All fish that survived after 48 h were alive after 60 days.

Indicative of a stress response, serum cortisol was elevated across all temperature treatments with no difference in concentrations between temperature treatments observed immediately after treatment completion [ANOVA $P>0.05$; Fig. 3(a)]. After 24 h, cortisol for treatments in which no mortality was observed, i.e. 4.3 and 12° C, increased by 44% [ANOVA $P<0.05$; Fig. 3(a)]. Cortisol for untreated fish decreased by 79% [ANOVA $P<0.05$; Fig. 3(a)].

Serum glucose was also elevated across treatments with concentrations significantly higher for the treatment with the highest temperature (16° C) and greatest mortality (75%) [ANOVA $P<0.05$; Fig. 3(b)]. After 24 h, glucose concentrations for the two treatments in which all fish survived, did not change significantly from what they had been immediately after treatment completion [ANOVA $P>0.05$; Fig. 3(b)].

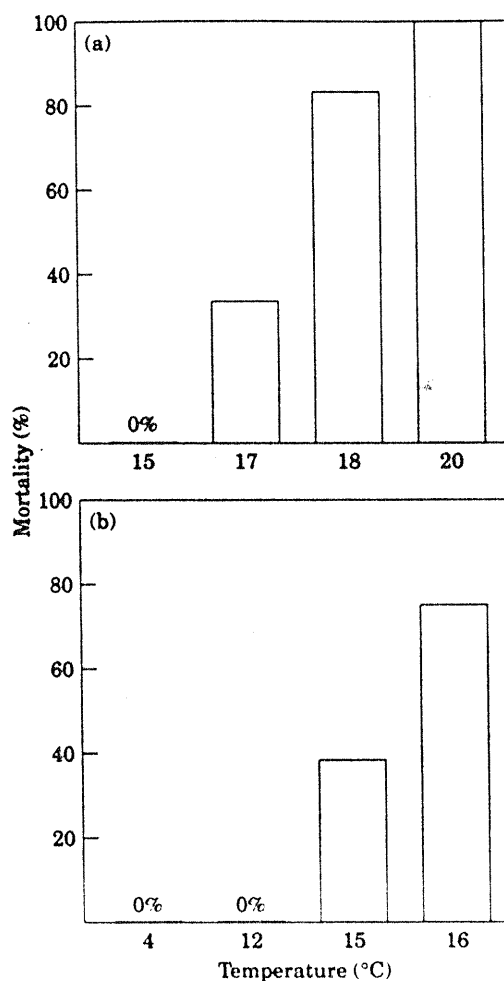


FIG. 2. Mortality (%) in sablefish 48 h after treatment with: (a) acclimation at 5.7° C then abrupt transfer to 15°, 17°, 18°, 20° C for 30 min, followed by 15 min in air ($n=6$) or, (b) acclimation at 4.8° C, towed 4 h, abrupt transfer to 4°, 12°, 15°, 16° C, followed by 15 min in air ($n=8$).

A clear relationship was apparent between serum lactate and temperature treatment with lactate increasing as temperature increased [ANOVA $P<0.05$; Fig. 3(c)]. After 24 h, lactate in the two treatments in which no mortality was observed decreased sharply [ANOVA $P<0.05$; Fig. 3(c)], and did not differ from untreated values [ANOVA $P>0.05$; Fig. 3(c)].

DISCUSSION

Exposing sablefish to an abrupt change in temperature exacerbated the effects of net towing and air exposure as manifested in increased mortality. The extent of the influence that temperature had on mortality depended on the magnitude of the change. An abrupt rise of 8° C or less resulted in no mortalities, while a

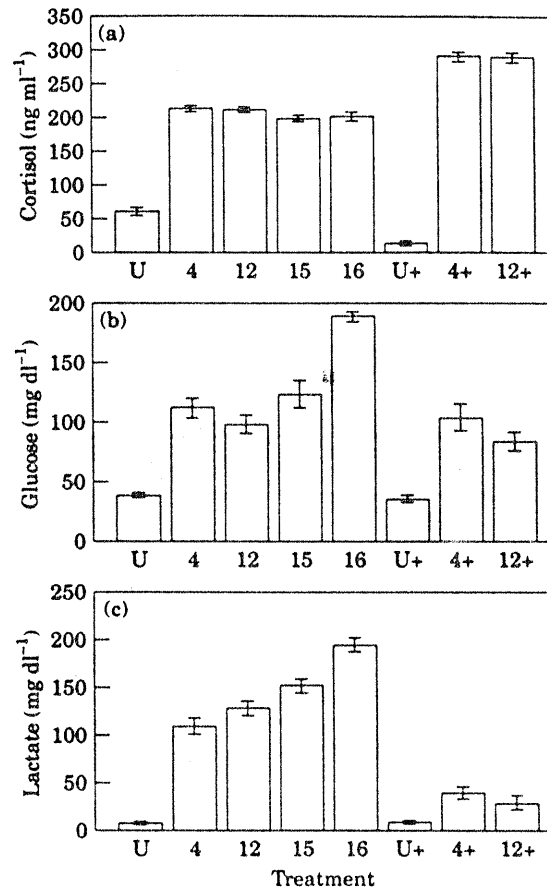


FIG. 3. Plasma concentrations in sablefish for: (a) cortisol (ng ml^{-1}); (b) glucose (mg dl^{-1}) and; (c) lactate (mg dl^{-1}). Fish treatments were: (U) untreated fish acclimated at 4.8°C ($n=6$); (4° , 12° , 15° , 16°C) fish treated as described in Fig. 2(b) ($n=9$, 9 , 6 , 6); (U+) untreated fish at 24 h (4.8°C ; $n=6$); ($4+$, $12+$) fish 24 h after treatment ($n=6$, 9). Values are mean \pm 1 s.e.

change of $10\text{--}11^\circ\text{C}$ caused mortalities of 38–75%. Even in the absence of any other stressors, an abrupt rise in temperature could induce mortality but the magnitude of change required to do so was several degrees higher.

It would appear from our results that the critical postcapture temperature for sablefish that reside and are trawl-caught at temperatures of $4\text{--}6^\circ\text{C}$, would be between 12 and 15°C . At 12°C no mortality occurred with all fish still surviving after 60 days; at 15°C , mortality was 38% after 48 h. With or without multiple stressors, the specific temperature or magnitude of change that a fish can tolerate depends in part on the acclimation temperature (Fry, 1971). In the present study, our aim was not to determine the upper incipient lethal temperature for the species but rather to apply acclimation and towing temperatures that were ecologically relevant for adult sablefish that reside off the north-west coast of the U.S.A. Further, the abrupt rise in temperature that fish were subjected to in this study was intended to simulate the postcapture temperature changes that

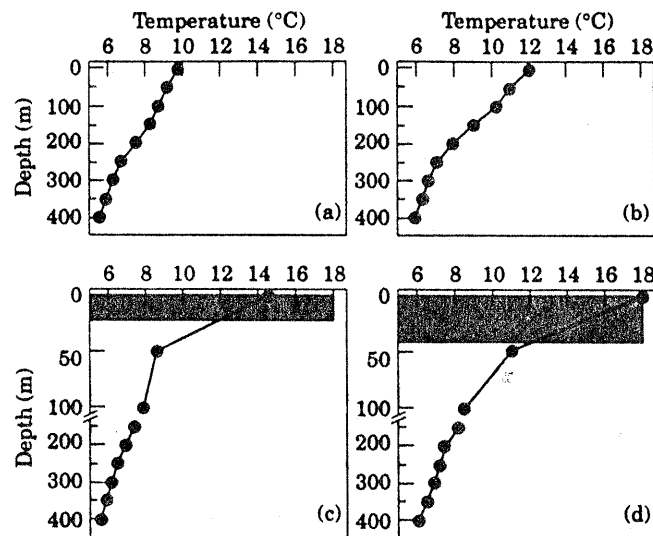


FIG. 4. Temperature increases with decreasing depth 70 km off the coast of Oregon, U.S.A. (adapted from Huyer & Smith, 1985). Profiles are for (a) average values for April, (b) values for April during El Niño year 1983, (c) values for July, (d) values for July during El Niño year 1983. Shaded regions in (c) and (d) indicate depths at which temperature was 12°C or greater, temperature at which sablefish that had been towed were thermally stressed.

sablefish might encounter as they are brought to the surface through the sharp thermocline that typifies the thermal regime in this region during summer and early autumn.

The seasonal variation in thermocline structure off the north-west coast of the U.S.A. is characterized by greater mixing during the winter and spring and the development of warmer temperatures and greater thermal stratification during the summer and autumn months (Huyer, 1977). This pattern holds true for average years and for years when the coastal ocean exhibits anomalous warming associated with El Niño ocean circulation patterns (Huyer & Smith, 1985; Rienecker & Mooers, 1986). For example, 70 km off the coast of Oregon, the warming of surface waters during the summer and fall results in a range of depths in which sablefish will be exposed to temperatures >12°C (Fig. 4), a temperature above which this study has determined that thermal stress effects are manifested. During average years, the critical depth is at ~25 m, while during El Niño years the depth may be ~45 m (Fig. 4).

It is obvious that the multiple stressors that are imposed on fish during actual fishing operations cannot be duplicated in the laboratory. Nonetheless, our results on the effects of temperature indicate clearly that temperature plays a major role in postcapture survival. In the absence of any other stressors, precise thermal limits were established for adult sablefish at the acclimation temperatures that were employed in the study. It was also clear that thermal limits would decrease as other stressors are added.

A clear pattern of increasing serum lactate was obtained when temperature stress was added to towing and air exposure. Held at 4 and 12°C for 30 min, lactate concentrations rose to 100–150 mg dl⁻¹, but then returned to prestress

(<50 mg dl⁻¹) concentrations within 24 h with all fish surviving for more than 60 days. At 15 and 16° C, lactate increased to 150–200 mg dl⁻¹ with mortalities ranging from 38 to 75%. No relationship was apparent between elevations in serum cortisol or glucose and mortality. These results suggest that serum lactate may serve as a surrogate for mortality. If further work confirms this, then the potential exists for being able to predict mortality from fish sampled at sea during actual fishing operations by relating circulating lactate from these fish to laboratory-derived standard curves regressing this variable against mortality.

When sablefish were transferred abruptly from 5.8 to 16° C it took ~30 min for body core temperature to reach levels near ambient. At 15 min after transfer, body core temperature was still ~3° C below ambient. This observation points up the importance of establishing the time course of temperature effects based on body core temperature (Spigarelli *et al.*, 1977), especially when attempting to develop strategies mitigating postcapture survival of non-targeted bycatch species. Presuming that adult sablefish in this study were returned to the sea in 15 min, body core temperature and hence the physiological effects of elevated temperature would have been at temperatures that were 3° C lower than they would have been at 30 min. Such a small temperature differential would be much less likely to induce mortality. Body core temperature would vary according to actual temperature, exposure time and size of the fish (Spigarelli *et al.*, 1977). Such determinations would be required for each species of interest and would be critical in defining the effect of at least one major stressor associated with fishing.

Fish towed for 4 h at 4 or 12° C and then held in air for 15 min experienced no mortality. This agreed with what we had observed in an earlier study with the towing and acclimation temperatures being 10–13° C (Olla *et al.*, 1997). These temperatures are within the range of non-lethal temperatures that were established in the present work.

In summary, elevated temperatures produced marked increases in serum lactate and mortality in adult sablefish, with or without the additional stress of towing. These effects indicate that temperature stress can be a significant factor in determining the effects of fishing practices on bycatch survival. Effects of elevated temperature in combination with stress associated with capture have not been considered directly before. Seasonal factors such as temperature should be included in calculations of mortality associated with fishing practices. Fishing effort could be adjusted to minimize the impact of exposure to seasonal thermoclines and high air temperatures that are neglected at present in management plans for bycatch survival. By making possible the direct measurement of effects of specific fishing practices *in situ*, the development of behavioural and biochemical assays for the effects of temperature and capture on stress in bycatch will be an important part of the effort to increase survival of bycatch.

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