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Acute exposure to a common suspended sediment affects the swimming performance and physiology of juvenile salmonids

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ABSTRACT

To study the effects of an acute exposure to turbidity generated by suspended sediment, we examined swimming performance (U_{crit}) and related metabolic parameters in individual and groups of juvenile trout at three different concentrations of calcium carbonate. To investigate differences among strains or provenience, we compared one strain of rainbow trout (*Oncorhynchus mykiss*; RBT) and one strain of brown trout (*Salmo trutta*; BNT) from a common hatchery and one RBT strain from a separate hatchery. In general, trout swum individually or in groups exhibited a decrease in U_{crit} as turbidity increased. Both RBT strains were more similar to each other and were impaired to a larger extent in swimming performance than BNT, which was less impacted. For groups, indicators of aerobic metabolism were elevated while those of anaerobic metabolism were depressed. Specifically, citrate synthase activities and glucose levels tended to be greater while plasma lactate and LDH activities were reduced. Lactate and LDH levels in individually swum trout under sediment exposure suggest a greater similarity of fish from the same provenience. We suggest that acute exposures to environmentally relevant turbidities generated by fine suspended sediment may cause a reduced U_{crit}, and that these changes may be related to changes in the utilization of aerobic and anaerobic pathways.

1. Introduction

Freshwater fish populations are declining drastically in many parts of the world (Duncan and Lockwood, 2001; Keiter et al., 2006; Venter et al., 2006). In Switzerland and Canada over 50% of the native freshwater-fish species are threatened (COSEWIC, 2003; Kirchhofer et al., 2007). In Switzerland, one of the formerly most abundant native fish species, brown trout (*Salmo trutta*; BNT), has decreased by more than 50% over the last twenty years (Burkhardt-Holm et al., 2005) and is on the verge of being listed as an endangered species (Kirchhofer et al., 2007). In Canada, some salmonid populations, such as the Okanagan chinook salmon (*Oncorhynchus tshawytscha*) and the Albertan Westslope cutthroat trout (*Oncorhynchus clarkii lewisi*), are classified as threatened (COSEWIC, 2011). It was previously hypothesized that increased erosion and sediment input could be responsible for some salmonid population declines (Burkhardt-Holm et al., 2005). Changes in climate and land use are expected to increase sediment input and suspended sediment concentrations, which in turn may increase exposure likelihood and severity for fish (for review see Scheurer et al., 2009).

Although salmonids generally prefer clear water and avoid suspended sediments (Armstrong et al., 2003; Ayllón et al., 2010), they often experience acute changes in turbidity and suspended sediment. For example, juvenile pacific salmon swimming from the Harrison River into the Fraser River move from a clear (~1 NTU) to a turbid (27–108 NTU) environment during their seaward migration (Gregory and Levings, 1998). Also, data on sediment input and load in alpine rivers show that the transport of fine sediments within a stream can occur in relatively short periods of time (Summer et al., 1994; Hamm et al., 1996), chiefly during heavy precipitation (e.g. Schindler Wildhaber et al., 2012). It is projected that such precipitation events, and hence also fine sediment transport in rivers, will increase in frequency and intensity in future (IPCC, 2007).

Even moderate levels of suspended sediment exposure not associated with gill damage can affect the respiratory ability of salmonids (Waters, 1995) and trigger an acute stress response (Michel et al., 2013). Some sediment-associated stress responses include elevated plasma glucose and plasma cortisol (Redding and Schreck, 1987; Servizi and Martens, 1992), increased cardiac output (Bunt et al., 2004), and changes in hematological parameters (Lake and Hinch, 1999; Michel et al., 2013). Suspended solids are also known to impact fish's feeding ability (e.g. due to impaired spotting of prey), routine activity, and stress levels (Berg and Northcote, 1985; Sweka and Hartman, 2001; De Robertis et al., 2003; Robertson et al., 2007; Awata et al., 2011).

While acute stress responses due to sediment exposure have been described (for review see Newcombe and Jensen, 1996; Kemp et al., 2011), no studies have been conducted on the possible effects of

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suspended sediments on swimming ability. The current study investigated the short-term effects of rapid changes in suspended sediment concentrations and resulting turbidity on swimming ability of three juvenile salmonid strains: rainbow trout (*Oncorhynchus mykiss*; RBT) and BNT from one hatchery and RBT from another. We used a common suspended sediment, calcite, to generate turbidity. Our first hypothesis was that exposure to fine suspended sediment would impair salmonid swimming performance, and that the impairment would be associated with physiological responses. Fish are thought to primarily use aerobic metabolism up to 85% of their critical swimming ability (U_{crit}), a speed thought to be a good estimate of their prolonged (hours-long) swimming ability, after which anaerobic metabolism is increasingly used until fatigue (Webb, 1971; Jain et al., 1997). We measured components of the aerobic pathway (citrate synthase; CS, the first enzyme of the citric acid cycle, and plasma glucose), and the anaerobic pathway (lactate dehydrogenase; LDH, activity and plasma lactate) immediately following the U_{crit} test (as in Goolish, 1991; Gamperl et al., 2002; Goertzen et al., 2011). We also measured post-exercise packed red blood cell volume (hematocrit; Hct), which can affect blood oxygen-carrying capacity and may be elevated in salmonids under stress (Gallaugher and Farrell, 1998) and with exposure to suspended solids (Redding et al., 1987).

Swimming performance tests have typically been carried out on individuals, in spite of the tendency of many fishes to school in a natural setting (Tierney et al., 2009), which is true of the juvenile salmonids we tested in this study (Shaw, 1978). Schooling benefits fish by increasing hydrodynamic efficiency (Weihs, 1973), which consequently, decreases metabolic oxygen consumption (Partridge, 1982; Abrahams and Colgan, 1985; Liao et al., 2003). In our study, in addition to testing fish individually, we also carried out U_{crit} tests on groups of five. Our second hypothesis was that fish swum in groups would swim faster than those swum individually, and be less sensitive to suspended sediment exposure. Basic data on the swimming performance and corresponding physiological parameters comparing the strains without influence of sediments were previously reported (Ralph et al., 2012).

The swimming physiology and performance in salmonids can vary depending upon provenience (i.e. geographic origin) and kinship (i.e. species affiliation; Hammer, 1995; Eliason et al., 2011; Hutchings, 2011). Furthermore, physiological responses to environmental stressors vary based on genetic, environmental or developmental factors (Barton, 2002; Liew et al., 2012). Because of this uncertainty in physiological performance determinants, we were unsure whether the effects of suspended sediment exposure would be more similar in the two strains of RBT from different origins, or the RBT and BNT from the same hatchery.

2. Materials and methods

2.1. Fish

One strain of RBT (*O. mykiss*, Salmonidae) named 'Mount Lassen' was sourced from Raven Brood Trout station ('RBT RC', Caroline, AB, Canada). This strain has been maintained in the facility without genetic input since 1989. We obtained the other strain of RBT, as well as a strain of BNT (*S. trutta*) from the Bow Habitat (Sam Livingston) Hatchery (Calgary, AB, Canada) ('RBT AC' and 'BNT AC', respectively), which sourced embryos of both species from Allison Creek Brood Trout Station (AB, Canada). The RBT are a Beity-Beaver Lake cross and the BNT are a Bow River strain (AB, Canada). Both have been genetically maintained without input from wild populations since 1977.

All fish were of similar age (6–9 months) and were held in six separate 177 L flow-through tanks on the same water source in the University of Alberta aquatics facility for at least two months prior to testing. Loading density did not exceed 45 fish per 0.5 m^3. Holding tanks were supplied with dechlorinated municipal water at 14–15 °C. The light: dark cycle mimicked seasonal changes and the fish experienced an average cycle of 16:8 h during the experimentation period. We fed the fish Nu-Way Trout Grower Finisher 5 mm pellets twice daily containing 5% fiber, 8% fat and 36% protein (Unifeed, Edmonton, AB, Canada). Fish were not fed for 24 h prior to testing. At testing period, all trout (n = 270) were 8.81 ± 0.08 cm (mean ± S.E.M.), 7.20 ± 0.22 g, condition factor (K) 0.99 ± 0.01. In detail, RBT RC (n = 85) were 7.97 ± 0.10 cm and 5.10 ± 0.17 g, with a K of 0.99 ± 0.02. RBT AC (n = 95) were 9.88 ± 0.11 cm and 10.8 ± 0.34 g, with a K of 1.11 ± 0.03. BNT AC (n = 90) were 8.47 ± 0.10 cm, 5.39 ± 0.18 g, with a K of 0.88 ± 0.02. Trials were completed from July to September 2010. All experiments were conducted in accordance with the Canadian Council of Animal Care guidelines and were approved by the University of Alberta Animal Care Committee (AUP #22).

2.2. Suspended sediment

Three concentrations of calcium carbonate ($CaCO_3$; calcite) powder (catalog no. C63-3, Thermo Fisher Scientific, Canada) were used to generate turbidity. Turbidity was measured in nephelometric turbidity units (NTU) (Davies-Colley and Smith, 2001). The low turbidity treatment (13 ± 3 NTU) was generated using 110 mg $CaCO_3$ L^{-1}, medium turbidity (29 ± 2 NTU) using 220 mg $CaCO_3$ L^{-1}, and high turbidity (62 ± 4 NTU) using 440 mg $CaCO_3$ L^{-1}. These turbidity levels are well within the range of values found in salmon-bearing rivers, especially during flood events (Gregory and Levings, 1998; Asselman, 1999; Tramblay et al., 2010; Schindler Wildhaber et al., 2012), and can also occur in Rocky Mountain streams following wildfires and salvage logging (Silins et al., 2009). Turbidity is commonly used to estimate suspended sediment loads (Lewis, 1996), and recent research suggests that stress may be evoked by turbidity, rather than by physical gill damage, at least for fine sediment (Newcombe, 2003; Michel et al., 2013). $CaCO_3$ is a naturally occurring suspended sediment that can be responsible for an appreciable percentage of turbidity. For example, $CaCO_3$ made up 32% of the average and 70% of the peak turbidity in the epilimnion of Otisco Lake (Effler and Johnson, 1987). Furthermore, $CaCO_3$ is often oversaturated in many major rivers (Cameron et al., 1995), including ones containing BNT (Neal et al., 2002), which suggests that wild salmonids naturally encounter water chemistry associated with saturation of dissolved $CaCO_3$ that would be similar to experimental conditions in our study.

Dechlorinated municipal tap water (Edmonton, AB, Canada) and the respective amount of $CaCO_3$ were mixed, and then added to the swim tunnel respirometer (STR; 10 L, Loligo, Denmark). The minimum flow in the STR was 5 cm s^{-1} which kept the $CaCO_3$ suspended (visual assessment). After each trial, the STR was cleaned and rinsed with clear municipal water until no trace of calcium carbonate powder particles was detected. The addition of $CaCO_3$ for suspended sediment trials did not alter the pH of the water. Control treatments consisted of trials with clear dechlorinated municipal water (8 ± 2 NTU) without any addition of $CaCO_3$ powder. The fish did not show any signs of distress during the experiments.

2.3. Experimental protocol

Swimming tests were conducted on individual fish (n = 90, RBT RC: n = 28, RBT AC: n = 32, BNT AC: n = 30) and on groups of five fish (n_{groups} = 36, n_{fish} = 180). Tests of individual fish were carried out under conditions with low, medium, or high concentrations of calcium carbonate. For group tests, only the low sediment concentration was used in order to allow for adequate visual monitoring of fish position. For transfer, individual fish was moved without air exposure using an opaque container placed underwater in the holding tanks and into the STR (Tierney, 2011). The oxygen concentration during the tests was ≥6 mg L^{-1} at all times. The STR was enclosed by a black curtain to limit external stimuli and minimize stress (as in Emran et al., 2010). Before starting the trials, fish were acclimated in the STR for 30 min at