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Source: Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 2009(2009) : 363-377

Published By: American Fisheries Society

URL: https://doi.org/10.1577/C09-039.1

Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 1:363–377, 2009

DOI: 10.1577/C09-039.1

[Article]

Behavioral and Physiological Response of White Sturgeon to an Electrical Sea Lion Barrier System

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Abstract.—Action agencies have encouraged the development of a modified electrical fish barrier system to deter upstream movements of California sea lions *Zalophus californianus* as a means to reduce their predation on returning adult Pacific salmon *Oncorhynchus* spp. within rivers along the West Coast of North America. Given that the barrier system does not discriminate which species will experience electrical shock, we studied the potential effects of the sea lion barrier on the survival, behavior, physiology, and injury of white sturgeon *Acipenser transmontanus*. Fish subjected to acute electroshock had high survival (100%). Conversely, fish that became entrained within the electric field and therefore experienced chronic electroshock had lower survival (93%). White sturgeon altered their behavior by spending significantly more time avoiding the area over the barrier when electrical power was applied as compared with controls. Fish that experienced acute electroshock spent more time remaining motionless, presumably recovering from physiological disturbance. Our results indicate that white sturgeon had significantly higher plasma lactate than controls and that lactate remained at elevated levels for at least 4 h after electroshock. Plasma glucose, ion concentrations (chloride, sodium, and potassium), and indicators of cell damage (plasma hemoglobin and enzyme activity of aspartate transaminase) did not differ between electroshocked fish and controls. We did not observe any notable hemorrhages or notochord injuries in white sturgeon that experienced electrical shock. Our results suggest that the location for the electrical barrier system should be rigorously examined before barrier deployment and that the dates, frequency, and duration of use should be further refined to ensure that negative effects on nontarget species such as white sturgeon are minimized.

Predation of California sea lions *Zalophus californianus* on returning adult Pacific salmon *Oncorhynchus* spp. along the West Coast of North America, particularly in the Columbia River basin, has become an increasing concern for biologists and fishery managers striving to conserve and restore threatened and endangered salmonid populations. Indeed, in November 2008, the National Marine Fisheries Service issued a Letter of Authorization allowing the Oregon Department of Fish and Wildlife, Washington Department of Fish and Wildlife, and Idaho Department of Fish and Game to lethally remove California sea lions deemed a threat to endangered salmonids (U.S. Department of Commerce 2008; U.S. District Court for the District of Columbia 2008). A potential alternate means to prevent the upstream movements of California sea lions is through the use of low electric fields conducted through a modified electrical fish barrier system (Bonneville Power Administration 2007), hereafter referred to as an electrical sea lion barrier system.

An electrical sea lion barrier system creates an electrical field within the water column to deter California sea lion movement upstream. The system is designed to operate at electrical power levels far below guidelines established by state and federal agencies for electrofishing of salmonid fishes (NMFS 2000; WSDOT 2006), and the system uses a pulsed direct current (DC) frequency lower than 15–30 Hz, which is intended to minimize injury to nontargeted fish (Reynolds 1996; Reynolds and Holliman 2004). Nevertheless, given that electrical fields have been applied in North America since the 1950s to alter and

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Received July 27, 2009; accepted September 23, 2009
Published online December 21, 2009

preclude the movement of aquatic fish species (Applegate et al. 1952; McLain et al. 1957; Swink 1999; Clarkson 2004), concerns have arisen among regulatory personnel and fisheries biologists regarding the effects that even a relatively low electrical field may have on nontarget species migrating through or residing within sites where such a system is tested or constructed.

White sturgeon *Acipenser transmontanus* are found in larger rivers, estuaries, and coastal areas along the West Coast of North America, including the lower Columbia River downstream of Bonneville Dam (Parsley et al. 2008). White sturgeon populations in the Columbia River basin provide recreational and commercial fisheries. Although white sturgeon are not the target of the electrical sea lion barrier, they would be considered vulnerable to its effects because of their anatomy and behavior. Because white sturgeon typically reach sizes of 3 m (Wydoski and Whitney 2003), they may be particularly vulnerable to an electric barrier because for a given voltage gradient, total body voltage increases with length, resulting in greater electroshock as fish size increases (Reynolds 1996). Although electrical field strengths that alter California sea lion behavior at the water's surface (Zeligs-Hurley and Burger 2008) appear to fall below lethal or injurious levels for salmonids (McMichael et al. 1998; Dwyer et al. 2001; Zydlewski et al. 2008), white sturgeon may be more vulnerable because they exhibit benthic habits (Wydoski and Whitney 2003). An electrical field at the electrodes decreases with linear distance (Reynolds 1996), so the electric field near the substrate (i.e., electrodes) will be greater than at the water's surface. Thus, white sturgeon may experience greater electroshock than California sea lions or salmonids. Lastly, fish typically exhibit galvanotaxis when subjected to pulsed DC, and as a result they typically swim toward the anode (Reynolds 1996), potentially exacerbating injurious effects.

During periods of electroshock, fishes may exhibit either lethal or sublethal responses. Lethal effects may result from electrical burns, hemorrhaging, and spinal and notochord injuries (Sharber and Carothers 1988; Hollender and Carline 1994; Sharber et al. 1994; Reynolds 1996; Schill and Elle 2000; Holliman and Reynolds 2002; Snyder 2003); however, electroshock may be administered at levels chosen to minimize injury to adult fish (Holliman and Reynolds 2002; Zydlewski et al. 2008). Nevertheless, sublethal stress caused by low levels of electricity may result in profound physiological disturbances (Roach 1999; Dwyer et al. 2001; Cho et al. 2002; Schreer et al. 2004). If sublethal stress is encountered during specific life history stages, it may negatively affect important physiological processes, such as individual fitness (Pankhurst and Van Der Kraak 1997, 2000; Contreras-Sanchez et al. 1998; Ostrand et al. 2004). However, sublethal effects of a low electrical field on white sturgeon physiology have not been documented.

Therefore, our goal was to determine whether the low electrical power produced by a prototype electrical sea lion barrier system significantly affects white sturgeon behavior or results in lethal or sublethal physiological disturbances before possible future installment or in situ tests. Specifically, our objectives were to (1) determine the behavioral responses of white sturgeon subjected to the electrical system pulser's "soft-start" pulse type, simulating an encounter when the system starts operating and the electrical field strength gradually increases to full power; (2) determine behavioral responses of white sturgeon subjected to the system's continuous operation, simulating the conditions white sturgeon may experience during peak salmon runs when California sea lion movements could potentially trigger the system to remain on for prolonged periods of time; and (3) determine the lethal or nonlethal physiological responses of white sturgeon subjected to acute electrical exposure by quantifying the magnitude of physiological disturbance and time required for recovery.

Methods

Fish rearing and tagging.—White sturgeon ($N = 90$) were purchased as newly hatched fry from Pelfrey's Sturgeon Hatchery (Troutdale, Oregon) in 1993, 1994, 1995, and 1996. Fry were produced from wild fish captured from the Columbia River downstream of Bonneville Dam. White sturgeon were maintained at Abernathy Fish Technology Center in concrete raceways (length × width × height, 22.3 × 2.4 × 0.81 m) at a water depth of 72 cm (water flows ≈ .01 m^3/s). In January 2008, before the onset of experimental trials, white sturgeon (mean fork length [FL] = 39.9 ± 2.5 cm; mean weight = 16.9 ± 0.3 kg) were marked dorsally with a 12-mm passive integrated transponder (PIT) tag (134.2 kHz International Organization for Standardization; Destron Fearing, Inc.). White sturgeon were maintained on an ad libitum diet of fish and feed. Food was withheld for 48 h before fish were used in an experimental trial. Water temperature (mean ± SE = 12 ± 1.3°C), dissolved oxygen (10 ± 0.8 mg/L), and conductivity (38 ± 1.5 mS/cm) were similar ($P > 0.05$) for all the experimental trials.

Electrical sea lion barrier system and PIT tag antennas.—The electrical sea lion barrier system and four PIT tag antennas were installed into a concrete raceway (length × width × height, 22.3 × 2.4 × 0.81 m; Figure 1). Smith-Root, Inc. (Vancouver, Washington)

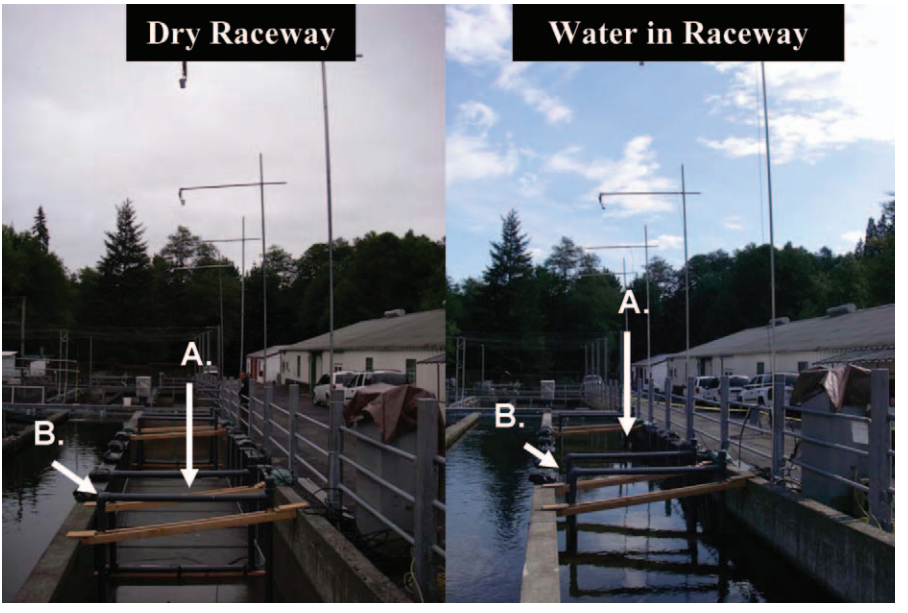

FIGURE 1.—Electrical sea lion barrier (A) and four passive integrated transponder tag antenna arrays (B) within a concrete raceway at Abernathy Fish Technology Center, Longview, Washington. The four electrode cables and temporary insulating medium are visible within the dry raceway.

provided and constructed the electrical sea lion barrier system, which was a scaled-down version of the system that was proposed to deter California sea lions in the main stem of the Columbia River near Bonneville Dam. The system consisted of two customized 1.5 programmable output waveform (POW) pulsators (Smith-Root) that converted incoming alternating current to the pulsed DC serving as the power supply for the electrodes. The output of the POWs was controlled and monitored with Fish Barrier Telemetry and Control System software via external computer systems and Control Smart Concentrator relays. Additional control of the output's power supply was provided by an external remote switch and control software that were developed as a safety feature for this project. The on/off switch was mounted on a length of cable to give observers the capability of interrupting and starting electric output remotely. Heavy-gauge insulated wire was used to connect the POW pulsators to the electrode arrays. The pulsers were operated by using either the soft-start or standard pulse type. The soft-start setting gradually increased the electric field strength over a 3-s period so that fish could move away from the system before it reached full power. Alternatively, the standard setting turned on the system at full power. Each pulser produced a 0.4-ms, 2-Hz waveform, resulting in an applied voltage of 530 V at a frequency of 2 pulses/s. The pulsers were connected to five electrode cables, evenly spaced across the raceway test location, and submerged over a rubber tarp insulating medium (i.e., length × width, 7.5 × 0.81 m) to contain the electric field within the raceway. The pulsers were manually turned on when prompted and created an additive electric field to the raceway water. Thus, the resulting electric field pattern was distributed from the raceway bottom to the surface (Table 1; Figure 2).

Point estimates of the electric field intensity (i.e., voltage gradient, V/cm) were quantified along the length of the electrode array. The voltage gradient across 10 cm (V/10 cm) of water was estimated via oscilloscope. Measures were taken every 0.3 m along the length of the electrode array and immediately upstream and downstream of the five electrodes. Measures were taken along three transects (along the left, right, and center of the raceway) and at three

TABLE 1.—Vertical distribution of the mean electrical field strength (SD in parentheses) measured at various distances from insulating medium within the raceway at Abernathy Fish Technology Center (M. Holliman, Smith-Root, Inc., personal communication).

Distance (cm)	*N*	Electric field (V/cm)
5.1	105	0.92 (0.78)
25.4	105	0.62 (0.48)
55.8	105	0.54 (0.41)

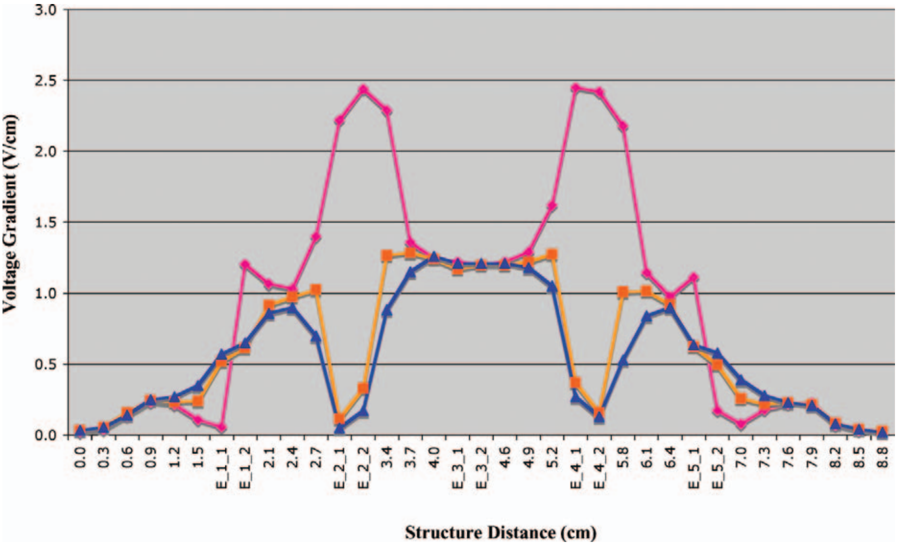

FIGURE 2.—Longitudinal profile (cross section) of median voltage gradient measured along the length of the electrical sea lion barrier system, including measurements taken on right and left sides of the electrodes. The parasitic electrodes at the upstream and downstream ends are represented by the distances "E_1_1, E_1_2" and "E_5_1, E_5_2" (*y*-axis). The electrodes represented by the distances "E_2_1, E_2_2" and "E_4_1, E_4_2" were charged (anode and cathode), and distance "E_3_1, E_3_2" represents the floating electrode (not connected; M. Holliman, Smith-Root, Inc., personal communication). Voltage gradient was measured at 5 cm (pink line), 25 cm (orange line), and 56 cm (blue line) off the bottom of the insulating medium.

depths (5, 25, and 56 cm). The measures were taken parallel to the direction of water flow and the general direction of fish travel (upstream or downstream). The voltage gradient measured across 10 cm was reported as the 1-cm average to provide a more standard unit of measure. The measurements were replicated once, providing six estimates (median) of the voltage gradient at each point along the length of the array.

The four pass-through PIT tag antennas were powered and tuned by a multiplexor transceiver (FS1001M; Destron Fearing). The transceiver unit stored each unique PIT tag code and the time and date of tag detection at each individual antenna. Two of the PIT tag antennas were located downstream of the electrical system's insulating medium (1.5 m apart from each other), and two were located upstream of the insulating medium (1.5 m apart from each other).

Behavioral responses of white sturgeon to the soft-start pulse type.—We conducted 20 individual experimental trials involving the soft-start pulse type ($N = 10$ replicates/treatment). During each trial, an individual naïve white sturgeon (mean length = 49.6 ± 4 cm FL; mean weight = 18.1 ± 0.47 kg) was stocked and confined to the downstream half of the raceway equipped with the electrical sea lion barrier system and four PIT tag antennas; the fish was allowed to acclimate for 24 h. Fish were confined to ensure that initial fish movement would mimic important upstream migration patterns commonly observed for spawning (Bemis and Kynard 1997; Pavlov et al. 2001; Brunch and Binkowski 2002; Hatin et al. 2002) and feeding (Bajkov 1951; Sulak and Randall 2002; Harris et al. 2005; Ruban 2005). After the 24-h acclimation period, the fish was released from confinement within the raceway with the electric system turned off. Once the treatment fish reached the downstream edge of the insulating medium (i.e., rubber tarp), the pulsers were triggered to turn on by using the soft-start pulse type. The soft start was not triggered for control fish. Treatment and control fish behavior was monitored and recorded via observations and PIT tag antennas.

White sturgeon behavior was recorded at 5-min intervals during the first hour of the experiment. White sturgeon behavior was separated into seven mutually exclusive categories (see Vibert 1963) and quantified as follows: (1) motionless (no movement); (2) search (moving but not orienting to or away from the electrical sea lion barrier system); (3) avoidance (approach and movement away from the electrical sea lion barrier system); (4) inhibition (inhibited swimming resulting from involuntary muscle contraction and relaxation in synchrony with the pulsed electric field); (5) galvanotaxis (swimming toward the anode as a result of the electrical field); (6) narcosis or stunned (relaxation of muscle); and (7) tetany (involuntary contraction of muscle [rigid] and lack of operculum movement). The total time spent over the system was defined as the sum of motionless, search, avoidance, inhibition, galvanotaxis, narcosis, and tetany behaviors. In addition, fish location and direction (i.e., upstream or downstream) were quantified.

All white sturgeon were monitored for mortality. Initial mortality was determined by immediate observations of excessive bleeding, loss of gill color, lack of respiration, inability of the fish to volitionally maintain equilibrium or swim after electroshock, or a combination of these. Delayed mortality was determined by visually inspecting the raceway for expired fish 24 h after electroshock to at least 11 d after each trial.

We employed a completely randomized design wherein the raceway stocked with an individual white sturgeon was considered to be our experimental unit and exposure of fish to the soft-start pulse type was considered to be the treatment. We used Kruskal–Wallis tests to evaluate differences among behavioral categories. Percentage data were arcsine–square root transformed to meet statistical assumptions. Significant Kruskal–Wallis tests ($P < 0.05$) were followed by Tukey-type mean separation tests for pairwise comparisons.

Behavioral response of white sturgeon to electrical barrier system continuous operation.—We conducted six individual experimental trials in which the electrical sea lion barrier was continuously operated ($N = 3$ replicates/treatment). During each trial, five naïve, PIT-tagged white sturgeon were stocked and confined at the downstream end of the raceway equipped with the electrical barrier and PIT tag antenna arrays. After a 24-h acclimation period, fish were released from confinement while the electrical sea lion barrier system was turned off. Behavior, location, swimming speed, and direction were visually monitored for the first hour and recorded for 24 h via the multiplexor transceiver and PIT tags. The fish were then confined to the downstream end of the raceway for 24 h. The electrical barrier was then turned on. After release from confinement, fish were visually monitored for behavior, location, swimming speed, and direction for the first hour, and these variables were recorded for 24 h via the multiplexor transceiver and PIT tags.

White sturgeon behavior was recorded at 5-min intervals during the first hour of the experiment and separated into the seven mutually exclusive categories defined previously. The total time spent over the system was defined as the sum of motionless, search, avoidance, inhibition, galvanotaxis, and tetany behaviors exhibited by each fish.

All white sturgeon were monitored for initial mortality as previously described. Delayed mortality was determined by visually inspecting the raceway for expired fish 24 h after electroshock through at least 15 d after each trial.

We employed a completely randomized design in which (1) the raceway stocked with five individual white sturgeon was considered to be the experimental unit and (2) continuous operation of the system was considered to be the treatment. Kruskal–Wallis tests were used to test for differences among behavioral categories. Percentage data were arcsine–square root transformed to meet statistical assumptions. Significant Kruskal–Wallis tests ($P < 0.05$) were followed by Tukey-type mean separation tests for pairwise comparisons.

Physiological response of white sturgeon subjected to acute electrical exposure.—A unique group of white sturgeon ($N = 27$) was assessed for physiological stress after acute electrical shock. Each experimental trial ($N = 6$ replicates) consisted of stocking and confining three individual white sturgeon in the area over the electrical sea lion barrier system electrodes. After a 24-h acclimation time, the electrical sea lion barrier system was turned on and the three white sturgeon were simultaneously subjected to a 3-min electroshock (standard pulse type; applied voltage of 530 V). The electric field and duration of electroshock were designed to simulate an actual shocking event in the field and previous experiments (i.e., behavioral responses to the soft-start pulse type and continuous operation). We then nonlethally collected blood from individuals by quickly (<10 s) capturing each fish, keeping the fish underwater (particularly the gills), and drawing blood via the caudal vessel (<30 s) following the methods of Suski et al. (2006). Previous work with bonefish *Albula vulpes* has shown this nonlethal blood sampling technique to be effective for generating fish recovery profiles without excessive sampling-induced disturbances (Suski et al. 2007). A nonlethal blood sample was collected from one of three fish immediately after electroshock. The two remaining fish were quickly transported to individual darkened chambers that were continuously supplied with aeration. These darkened chambers act as sensory deprivation environments and allow fish to recover from stressors. After recovery for 1 or 4 h ($N = 6$ white sturgeon per time period), fish were bled as described above. Finally, an additional group of white sturgeon ($N = 9$ fish) were placed in the individual darkened chambers (without receiving any electroshock treatment) and were allowed to acclimate to the chambers for 24 h. After the acclimation period, these white sturgeon were quickly collected from their individual chambers and sampled for blood as described above, thereby acting as a control group to account for any handling-induced physiological disturbances. All white sturgeon were then placed in a common holding raceway, where they were monitored for mortality (in a manner identical to that described above) for at least 15 d.

Whole blood from each individual was separated into three vials. The vials were then immediately brought into the laboratory and centrifuged for 5 min at 4°C. The plasma was then decanted into three separate vials per fish and then frozen and stored at −80°C. Plasma samples were assayed for concentrations of glucose and lactate (following the methods of Lowry and Passonneau 1972) by using a microplate spectrophotometer (Spectra Max Plus 384 Model 05362; Molecular Devices, Union City, California). Plasma hemoglobin (QuantiChrom Hemoglobin Assay Kit DIHB-250; BioAssay Systems, Hayward, California) and ions (Na^+, K^+) were determined by using a digital flame photometer (Model 2655–00; Cole-Parmer Instrument Company, Chicago, Illinois). Plasma chloride (Cl^-) concentration was determined by using a digital chloridometer (Model 4425000; Labconco, Kansas City, Missouri). The enzyme activity of aspartate transaminase (AST) in plasma (enzyme number 2.6.1.1; IUBMB 1992) was quantified by using standard kinetic spectrophotometric techniques based on the methods of Yagi et al. (1985). The AST enzyme is involved in oxidative reactions primarily within liver tissue, and elevated AST activities in the blood of fishes are indicative of damage or rupturing of liver cells (Casillas et al. 1982).

In addition, five white sturgeon were visually evaluated for internal injuries after electroshock. Five individual white sturgeon were stocked and confined in the area over the electric system. After a 24-h acclimation period, the electric system was turned on and the five white sturgeon were simultaneously subjected to a 3-min electroshock (standard pulse type; applied voltage of 530 V). Fish were immediately euthanized with an overdose of tricaine methanesulfonate (MS-222) and refrigerated for a 24-h period to reduce fillet-related bleeding. Because white sturgeon skeletons are not visible on radiographs, the severity of injury was evaluated by filleting both sides of each fish to expose axial skeleton and musculature following the methods of Reynolds (1996) and Holliman and Reynolds (2002). The notochord was separated and visually examined for damage (i.e., notochord rupture). Fillets were examined for hemorrhages, observed hemorrhages were rated by severity based on worst hemorrhage observed (class 0 = no apparent hemorrhage; class 1 = one or more wounds in the muscle, separate from the notochord; class 2 = one or more small wounds [$\leq$width of two notochordal segments] on the notocord; class 3 = one or more large wounds [$>$width of notochordal segments] on the notochord; Reynolds 1996). The fillet and notochord were photographed, and images containing hemorrhages were digitally enhanced by using Image Pro 6.0 software to quantify the size of each hemorrhage.

Differences were assessed between treatment and control fish for each response variable (glucose, hemoglobin, lactate, plasma ions [Na^+, K^+, Cl^-], and AST activity). We employed a completely randomized design in which each individual white sturgeon was considered to be the experimental unit and electrical field strength was considered to be the treatment. Kruskal–Wallis tests were used to test for differences among physiological variables between electroshocked white sturgeon and controls. Significant ($P < 0.05$) Kruskal–Wallis tests were followed by Tukey-type mean separation tests for pairwise comparisons.

Results

Behavioral Responses of White Sturgeon to the Soft-Start Pulse Type

We observed no initial mortality of white sturgeon subjected to the electrical sea lion barrier system's soft-start pulse type. In addition, no delayed mortalities were observed after release or throughout the duration of the study.

White sturgeon behavior was altered when fish were subjected to the soft-start pulse type associated with the electrical sea lion barrier system (Table 2). Control fish and treatment fish spent the majority of time engaged in search behavior. However, white sturgeon subjected to the soft-start pulse type spent significantly less time over the electrical system than controls (Figure 3A). White sturgeon that encountered the soft-start pulse type more frequently avoided the barrier system (mean = 61%) than swam past it (mean = 39%), whereas control fish more frequently swam past the system (mean = 81%) than avoided it (mean = 19%; Figure 3B). White sturgeon passed the electrical system significantly faster when subjected to the soft-start pulse type (Kruskal–Wallis: $F = 40.72$, $P < 0.01$; Figure 3C). Eighty percent of the white sturgeon that swam through the electrical field exhibited inhibition (mean ± SE = 25 ± 17 s/h). Only one treatment fish (6.6%) displayed galvanotaxis (3.5 ± 3.5 s/h), and only one treatment fish (6.6%) demonstrated narcosis (2.7 ± 2.7 s/h).

Control fish continually swam the length of the raceway throughout the observational period (Figure 4A). Conversely, white sturgeon subjected to the soft-start pulse type approached the electric system during the initial portion of the observational period, resulting in the fish either avoiding or passing the electrical system. During the latter portion of the observational trial, treatment fish approached the electrical system

TABLE 2.—Mean duration (s/h; SE in parentheses) of various white sturgeon behaviors exhibited during a 1-h observation period by control fish or by fish that were subjected to the soft-start pulse technology associated with an electrical sea lion barrier structure in raceways (N/A = not applicable).

			Contrasts	
White sturgeon behavior	Soft start	Control	*F*	*P*
Motionless	0.0 (0.0)	712.5 (328.8)	18.53	<0.01
Crossing barrier	54.4 (16.1)	816.8 (110.3)	31.63	<0.01
Total over barrier	178.7 (43.6)	1,154.2 (250.6)	18.43	<0.01
Search	2,708.8 (329.5)	2,445.8 (250.6)	2.46	0.13
Avoidance	118.1 (32.4)	337.4 (213.9)	9.29	<0.01
Inhibition	25.0 (17.1)	0.0 (0.0)	28.59	<0.01
Galvanotaxis	3.5 (3.5)	0.0 (0.0)	1.00	0.33
Narcosis	2.7 (2.7)	0.0 (0.0)	1.00	0.33
Tetany	0.0 (0.0)	0.0 (0.0)	N/A	N/A

less frequently and instead returned to either the upstream or downstream end of the raceway and engaged in search behavior (Figure 4B; Table 2). As a result, fish in the soft-start pulse type treatment spent less time using the entire raceway than control fish. Treatment fish, which presumably experienced electroshock, spent significantly more time motionless off the barrier than controls, particularly during the later observational time periods (Figure 4C).

Behavioral Response of White Sturgeon to Continuous Operation of the Electrical Sea Lion Barrier System

We observed no initial mortality for white sturgeon subjected to the electrical sea lion barrier system during continuous operation. However, 4 of the 15 white sturgeon subjected to the continuous operation of the system exhibited narcosis while the system was turned on. One of the four fish was not entrained over the system. Three of the four fish remained on the barrier and exhibited narcosis (mean ± SE = 22.4 ± 1.4 h) for the duration of the trial. After the electric system was turned off, two of these three fish entrained over the barrier were able to recover and survived. The remaining fish died approximately 40 h after the completion of the trial.

White sturgeon behavior was altered when subjected to continuous operation associated with the electrical sea lion barrier system (Table 3). Control fish continually swam the length of the raceway throughout the observational period. Control fish and treatment fish spent the majority of time engaged in search behavior. However, white sturgeon subjected to the continuous operation treatment spent significantly less time over the electrical system than controls (Figure 5A), regardless of the time of day (Kruskal–Wallis: $F = 11.6$, $P = 0.002$; Figure 6). White sturgeon that encountered the continuously operating electric system more frequently avoided the system (mean = 78%) than swam past it (mean = 22%), whereas control fish more frequently swam past the system (mean = 58%) than avoided it (mean = 42%; Figure 5B). As a result, treatment fish restricted their movement to a smaller portion of the raceway than control fish. White sturgeon that did pass over the system did so much more quickly when the system was continuously operated

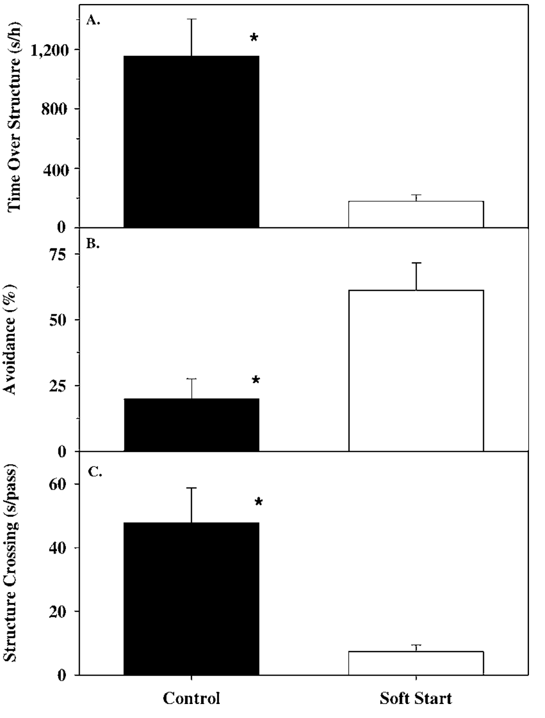

FIGURE 3.—Behaviors (mean ± SE) of white sturgeon within the raceway for control fish and fish subjected to the soft-start pulse type: **(A)** time for which the fish occupied the water column above the electrical barrier system; **(B)** percentage of observed events in which the fish approached the electrical system, turned, and returned as opposed to passing over the system; and **(C)** time taken by the fish to cross the system. Asterisks indicate significant ($P < 0.05$) differences between control and treatment fish.

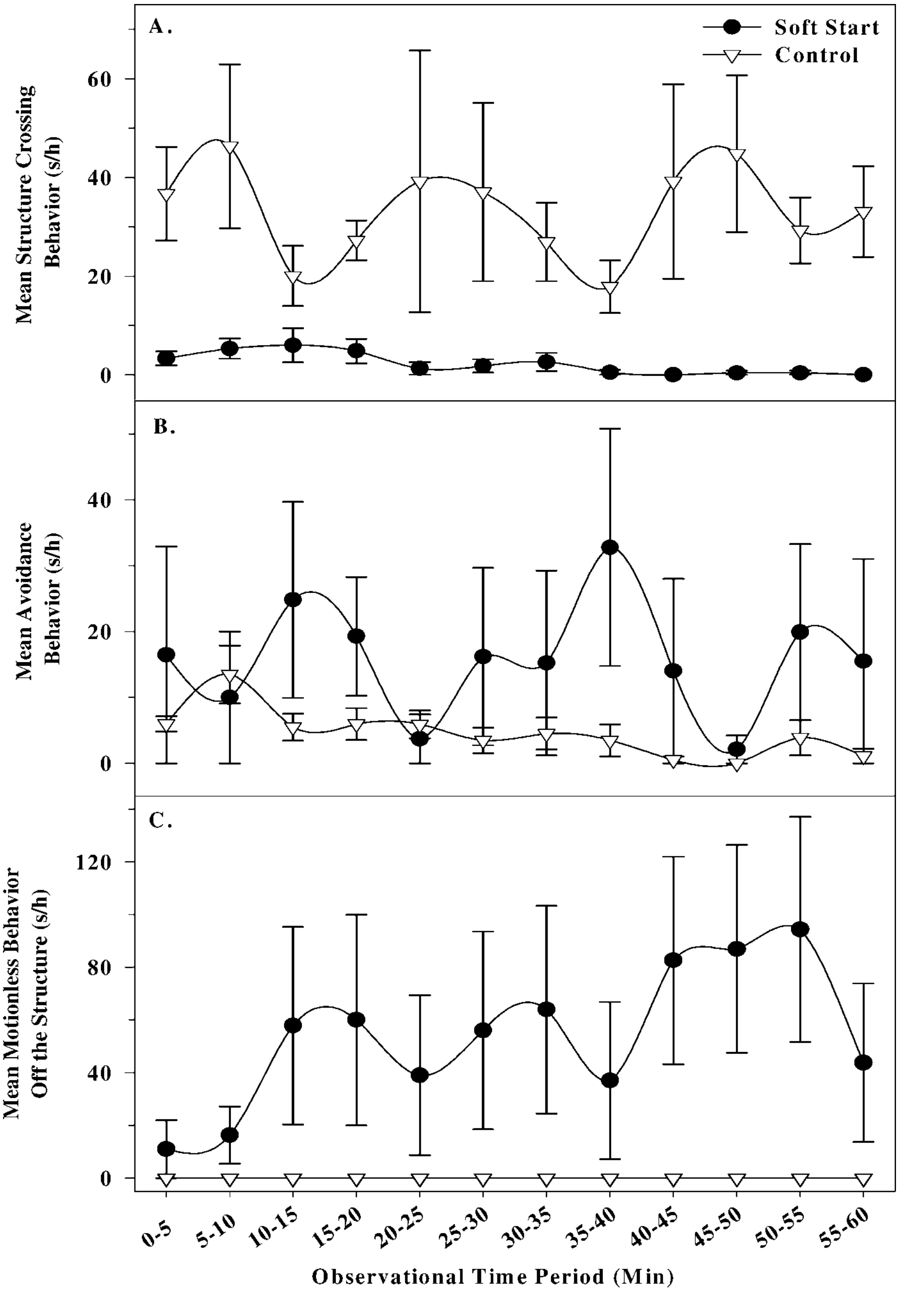

FIGURE 4.—Duration (mean ± SE) of various white sturgeon behaviors for each 5-min interval during 1-h observation periods for fish subjected to the soft-start pulse type (circles) and for control fish (triangles).

(Kruskal–Wallis: $F = 13.5$, $P = 0.02$; Figure 5C). One-hundred percent of the white sturgeon that experienced the electrical field exhibited inhibition (mean ± SE = 33.7 ± 9.4 s/pass), whereas galvanotaxis was only observed six times (49.7 ± 17.0 s/pass) and narcosis was only observed four times (1,381.6 ± 668.2 s/pass).

Physiological Response of White Sturgeon Subjected to Acute Electrical Exposure

White sturgeon were sublethally stressed after being subjected to electroshock, although they did not exhibit significant cell damage in comparison with controls (Table 4). Plasma lactate was significantly higher in

TABLE 3.—Mean duration ($s \cdot fish^{-1} \cdot h^{-1}$; SE in parentheses) of various white sturgeon behaviors exhibited during a 1-h observation period by control fish and by fish subjected to the continuous operation of an electric sea lion barrier structure in raceways (N/A = not applicable).

			Contrasts	
White sturgeon behavior	Continuous	Control	*F*	*P*
Motionless	353.7 (353.7)	228.0 (228.0)	0.05	0.83
Crossing barrier	8.5 (4.5)	354.5 (156.0)	13.50	0.02
Total over barrier	71.3 (28.5)	797.0 (173.7)	13.50	0.02
Search	2,714.5 (454.2)	2,575.0 (67.0)	0.38	0.57
Avoidance	42.9 (28.4)	401.7 (175.8)	13.50	0.02
Inhibition	29.2 (13.9)	0.0 (0.0)	27.00	<0.01
Galvanotaxis	19.9 (16.1)	0.0 (0.0)	3.69	0.13
Narcosis	460.5 (181.9)	0.0 (0.0)	27.00	<0.01
Tetany	0.0 (0.0)	0.0 (0.0)	N/A	N/A

fish subjected to electroshock than in controls (Table 4). Plasma lactate remained at elevated levels for at least 4 h after electroshock (Figure 7). Mean plasma hemoglobin concentrations after electroshock increased eightfold relative to controls, but the response was quite variable across individuals and changes were not significantly different from the control values (Table 4). There were no significant differences in plasma glucose across control and electroshocked white sturgeon (Table 4). Likewise, plasma ion concentrations (i.e., chloride, sodium, and potassium) did not significantly differ between electroshocked fish and controls. The AST activity in the plasma of electroshocked white sturgeon did not significantly differ from that in controls. One fish died approximately 95 h after experiencing the electroshock.

There were no apparent notochord injuries or hemorrhages for four of the five white sturgeon that were euthanized after electroshock. One of the five fish had a hemorrhage located within the dorsal muscle posterior to the dorsal fin insertion (Figure 8). This class-1 hematoma was 0.67 cm wide and less than the length of two notochordal segments (3.06 cm).

Discussion

Our results suggest that the employment of the electrical sea lion barrier may result in altered microhabitat use; changes in migratory, feeding, and reproductive behavior; and mortality of white sturgeon, particularly during periods of continuous operation. Alternatively, use of the soft-start pulse type coupled with intermittent operation of the electric system may reduce the probability that white sturgeon will become entrained on the system and suffer the chronic electroshock that may result in mortality. White sturgeon that experience acute electroshock will most likely recover with minimal cell or tissue damage. We suggest that the system's test location should be thoroughly scrutinized before its deployment and that the duration, frequency, and timing of operation should be considered to minimize the potential effects on the lower Columbia River white sturgeon population. Our results suggest that employment of the electrical sea lion barrier should be considered as a means to merely reduce, rather than eliminate, California sea lion predation on salmonids.

Our results suggest that white sturgeon routinely avoid and do not pass over (61–78%) the barrier system when it is operational; therefore, seasonal and daily migrations, movements, and site fidelity of white sturgeon may be negatively influenced by the system's location and timing of operation. For example, placing and operating the system downstream of river kilometer (rkm) 232 on the Columbia River may affect recruitment by altering spawning migrations, particularly given that reproductively active white sturgeon move upstream (to rkm 232) from April to June (Bell 1973; McCabe and Tracy 1994; Paragamian and Kruse 2001). Additionally, growth and survival of nonspawning white sturgeon may be altered because these individuals move downstream during the spring and upstream in the fall, presumably engaging in continuous feeding (McKinley and Power 1992; Findesis 1997; Parsley et al. 2008). White sturgeon in the lower Columbia River also make daily migrations from daytime (mean depth = 21.1 m) to nighttime (mean depth = 15 m; Parsley et al. 2008), similar to Atlantic sturgeon *A. oxyrhinchus* (Moser and Ross 1995; Collins et al. 2000; Hatin et al. 2002), green sturgeon *A. medirostris* (Erickson et al. 2002), and gulf sturgeon *A. oxyrhinchus desotoi* (Mason and Clugston 1993; Foster and Clugston 1997), and this should also be considered. Finally, placement and operation of the system should avoid areas where white sturgeon commonly exhibit site fidelity (Parsley et al. 2008). Proper placement of the system and thoughtful consideration regarding the timing of its operation

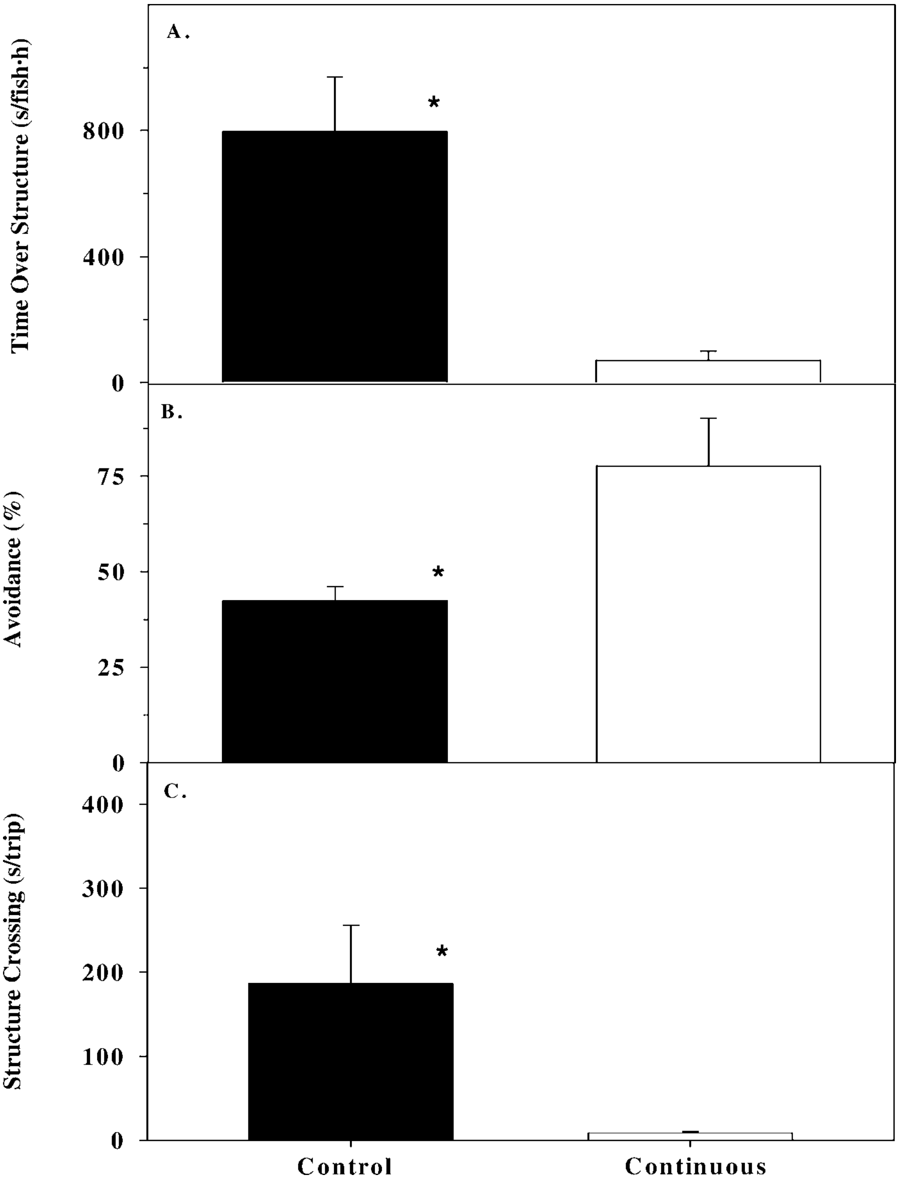

FIGURE 5.—Behaviors (mean ± SE) of white sturgeon within the raceway for control fish and fish subjected to continuous operation of an electrical sea lion barrier system for 24 h: **(A)** time for which the fish occupied the water column above the electrical system; **(B)** percentage of observed events in which the fish approached the electrical system, turned, and returned as opposed to passing over the system; and **(C)** time taken by the fish to cross over the system. Asterisks indicate significant ($P <$ 0.05) differences between control and treatment fish.

should circumvent the majority of potentially negative alterations to migratory behavior.

Utilization of the soft-start pulse type did not result in lethal electroshock of white sturgeon even though 39% of the fish passed over the barrier and most exhibited inhibition. While the soft-start pulse type did not eliminate fish electroshock and sublethal stress, as indicated by motionless behavior and elevated plasma lactate, it afforded recovery time, allowing the fish to move off the system. As a result, no fish perished due to the acute electroshock associated with the soft-start pulse type. Conversely, when the barrier was operated continuously, a few white sturgeon became entrained within the electric field in a state of narcosis and thus

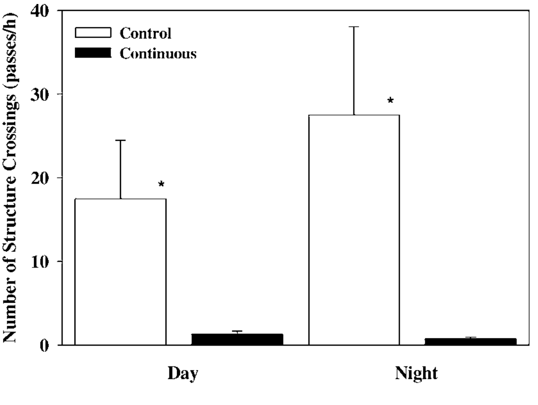

FIGURE 6.—Number of times (mean ± SE) white sturgeon passed over the electrical sea lion barrier system when it was either continuously operated or turned off during daylight or nighttime hours. Asterisks indicate significant ($P < 0.05$) differences between control fish and fish subjected to continuous barrier operation for each time of day.

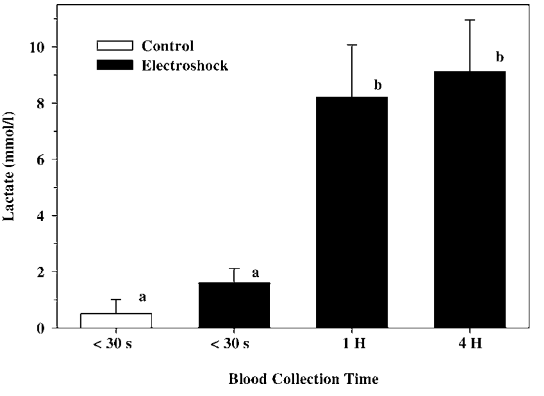

FIGURE 7.—Plasma lactate (mmol/L) in white sturgeon subjected to an applied voltage of 530 V for 3 min. A nonlethal blood sample was collected from treatment fish immediately after electroshock, 1 h after recovery, or 4 h after recovery ($N = 6$ fish per time period) and from control fish ($N = 9$ fish). Blood collection times with different letters had significantly different ($P < 0.05$) plasma lactate values.

were unable to recover and leave the field. As a result of this chronic exposure, one white sturgeon perished. Although our study used relatively few fish, our mortality estimates (4.5%) were similar to reported natural mortality for white sturgeon in the lower Columbia River (4.2–9.0%; Beamesderfer et al. 1995). We hypothesize that any mortality occurring from the electric barrier system would be additive to natural mortality estimates. Given that chronic electroshock can result in mortality and that white sturgeon experience electroshock regardless of employment of the soft-start pulse type, particular attention should be given to future engineering refinements, such as intermittent operation and a more prolonged soft start that ensures ample recovery time for white sturgeon to escape the electric field. Since the size of the electrical sea lion barrier system and associated sweeping water

TABLE 4.—Plasma parameters (mean with SE in parentheses) measured for white sturgeon subjected to an applied voltage of 530 V for 3 min. A nonlethal blood sample was collected from fish immediately after electroshock, 1 h after recovery, or 4 h after recovery ($N = 6$ white sturgeon per time period). Control fish ($N = 9$ fish) did not receive any electroshock.

				Contrasts	
Plasma parameter	Sample	Electroshocked	Control	*F*	*P*
Glucose (mmol)	Initial	5.4 (0.8)	8.6 (3.5)	1.76	0.18
	1 h	14.6 (5.3)			
	4 h	10.1 (1.6)			
Hemoglobin (mg/dL)	Initial	75.7 (9.6)	250.9 (179.1)	0.39	0.76
	1 h	663.8 (364.9)			
	4 h	94.0 (23.3)			
Lactate (mmol)	Initial	1.5 (0.5)	0.5 (0.5)	14.03	<0.01
	1 h	8.2 (1.8)			
	4 h	9.1 (1.8)			
Chloride (mEq/L)	Initial	106.3 (2.7)	102.7 (1.7)	1.37	0.27
	1 h	108.1 (2.2)			
	4 h	108.1 (3.8)			
Sodium (mEq/L)	Initial	184.1 (10.8)	192.5 (13.8)	0.31	0.81
	1 h	182.6 (7.8)			
	4 h	178.5 (10.1)			
Potassium (mEq/L)	Initial	5.6 (0.4)	5.0 (0.3)	0.34	0.79
	1 h	4.9 (0.3)			
	4 h	4.6 (0.5)			
Aspartate transaminase (units/L)	Initial	3.6 (1.3)	4.6 (1.7)	0.80	0.51
	1 h	4.5 (1.5)			
	4 h	2.0 (0.5)			

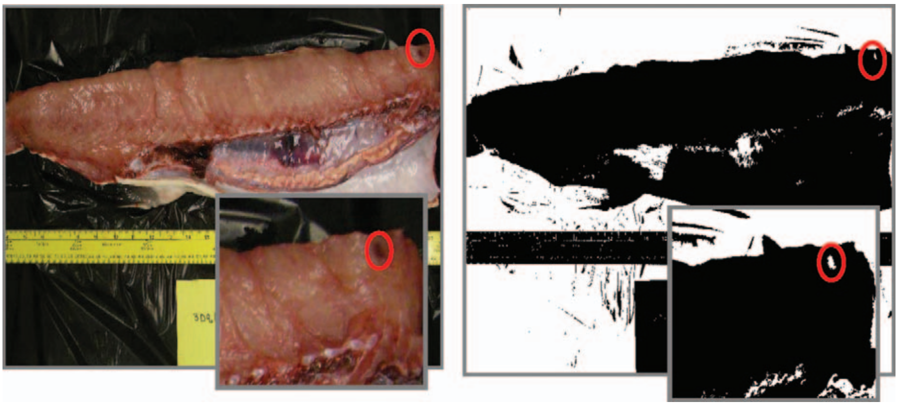

FIGURE 8.—Hematoma (circled in red) in a white sturgeon after the fish was subjected to an applied voltage of 530 V for 3 min. The image on the left is the original digitized image, whereas the image on the right has been enhanced via a segmentation filter to separate the hematoma from background noise that occurs in most acquired images.

velocities are unknown, we suggest that these future engineering refinements take into account (1) the mean time for which fish remained in narcosis (2.7 s/h) and (2) swimming speeds (range = 0.20–0.83 m/s; Geist et al. 2005; Parsley et al. 2008) to ensure that fish are indeed able to recover and move out of the electric field before it comes back on. Even small reductions in mortality are important because they are directly related to large increases in numbers given the long life span of white sturgeon (Paragamian et al. 2005, 2008) and the species' relevance to commercial and recreational fisheries.

If refinements in the system's operation can be accommodated, resulting in only acute white sturgeon electroshock, fish should exhibit minimal physiological disturbance. Collectively, our results show that white sturgeon are physiologically resilient to short periods of electroshock even though our study did not fully encapsulate complete physiological recovery for plasma lactate. In the current study, plasma lactate concentrations in white sturgeon at 1–4 h after electroshock were approximately 8–9 mmol. Crocker and Cech (1998) found that white sturgeon exposed to 96 h of hypercapnia exhibited plasma lactate values below 0.5 mmol, while Baker et al. (2008) showed that lake sturgeon *A. fulvescens* sampled immediately after capture and radio tag implantation had a plasma lactate level of approximately 6.5 mmol (range = 2.7–12.1 mmol). Plasma lactate indicates anaerobic metabolism (i.e., insufficient oxygen delivery to tissues) that most likely resulted from muscle contractions associated with escape response, inhibition, and galvanotaxis coupled with narcosis and minimal water and thus oxygen exchange through the gills. We hypothesize that the motionless behavior we observed in fish subjected to the soft-start pulse type and acute electroshock was a result of plasma lactate recovery; however, further experimentation would be required to substantiate this.

Although the other biochemical indicators of sublethal stress that we measured in our study did not suggest physiological disturbance after acute electroshock, fish that experience chronic exposure will likely yield different results. Freshwater fishes exposed to chronic, prolonged stressors can exhibit ion loss; however, our results suggest that white sturgeon maintain ion concentrations, presumably because of the lack of chronic stress. Likewise, plasma glucose, part of the secondary stress response in fishes, remained between 10.1 and 14.6 mmol at 1–4 h after electroshock and did not differ from that of control fish in our study. Crocker and Cech (1998) showed that plasma glucose concentrations of white sturgeon did not increase above 3.5 mmol even after 96 h of hypercapnia, whereas capture, handling, and tagging of lake sturgeon resulted in plasma glucose concentrations of approximately 9 mmol (range = 3–18 mmol; Baker et al. 2008). We hypothesize that white sturgeon entrained within the electrical field for relatively long periods of time, like those in our continuous operation experiment, will probably lose plasma ions and have altered glucose levels; however, further experimentation will be required for support.

Lastly, the AST activity and hemoglobin in the plasma did not suggest that liver cells or red blood had been ruptured, and the lack of large hematomas or notochord rupture within the fillets indicates that no significant tissue damage occurred. In the current study, the activity of AST in the plasma of white sturgeon after electroshock did not vary from control values and remained at or below 4.5 units/L at all sampling points. In comparison, smallmouth bass *Micropterus dolomieu* that experienced barrotrauma during a live-release angling tournament displayed plasma AST activity of approximately 60 units/L (Morrissey et al. 2005). The response of white sturgeon to brief electroshock in the current study was highly variable, with an eightfold increase in plasma hemoglobin at 1 h after electroshock; however, the response was quite variable across individuals, and changes were not significantly different from control values. Elevated concentrations of plasma hemoglobin returned to control values after 4 h of recovery, suggesting that any hemolysis was corrected after a few hours. While we did observe a single hematoma, the fish most likely would have recovered if it had not been euthanized (sensu Sharber et al. 1994; Schill and Elle 2000). Although further examination is needed to refine specific recovery times associated with various exposure periods, our results suggest that the electrical sea lion barrier system, if deployed, should be operated intermittently to ensure that physiological disturbance remains minimal and that fish recover thoroughly before potentially being subjected to additional electroshock.

Acknowledgments

This project was funded through a grant provided by the U.S. Department of Energy, Bonneville Power Administration, Division of Fish and Wildlife (Project Number 2007-524-00). We thank Smith-Root, Inc. and M. Holliman for construction and installation of the abatement system and for collecting and providing the electrical data. We thank B. Kennedy, J. Poole, J. Holmes, J. Samagaio, and M. Van Landeghem for assistance with data collection and processing. We also thank J. Brady for administrative support. We acknowledge the review of earlier drafts of this article by C. Burger and P. Crandell. We are indebted to M. Mesa, the editors, and the anonymous reviewers for their thoughtful comments regarding this article. The findings and conclusions in the report are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

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