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Reducing Electrofishing-Induced Injury of Rainbow Trout

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Abstract.—We conducted three sets of experiments to determine aspects of pulsed direct current responsible for high incidence of spinal injury in electrofished rainbow trout *Oncorhynchus mykiss* and to test the electrotaxis efficiency of a new complex pulse pattern (low-frequency bursts of high-frequency pulses). In the first set of experiments, we energized three types of anodes with current pulsed at 60 pulses per second (pps) to produce fields with relatively low, intermediate, or high voltage gradients near the anode. Results showed no direct relationship between voltage gradient and injury rate. In the second set of experiments, we tested the complex pulse pattern and four other pulse frequencies using a spherical anode. The results demonstrated a low injury rate with the complex pulse pattern and a curvilinear increase in spinal injuries with rising pulse frequency. Moderate to high pulse frequencies, therefore, rather than high voltage gradients, appear to be the primary cause of spinal injury. We suggest that more fish injuries are seen at higher pulse frequencies because these injuries are caused by myoclonic jerks associated with shock-induced epileptic seizures, and such seizures develop more rapidly at higher frequencies than at lower frequencies. In the third set of experiments, we found the electrotaxis efficiency of the complex pulse pattern was similar to those of regular 60 pps and 30 pps patterns. The complex pattern, therefore, combined low incidence of injury with good electrotaxis and narcosis.

Electrofishing is the technology of capturing fish by producing in water an electric field of sufficient intensity to cause strong neurological responses (Vibert 1967). In most electrofishing practice today, pulsed direct current (DC) is used because it requires less power than unmodulated DC. Alternating current (AC) is not preferred because it is known to cause injuries in fish (Hauck 1949) and does not elicit the appropriate electrotaxis needed for efficient electrofishing (Van Harreveld 1938; Haskell 1954; Vibert 1963).

As fish experience electrotaxis, moving through the electric field toward the anode (Reynolds 1983), the voltage gradient increases virtually exponentially (Novotny and Priegel 1974). This increase causes neuromuscular responses to intensify and predictable behavioral patterns to result. At the lowest level of shock response, a fish moves through the water in random directions, a phenomenon generally referred to as fright. As the fish experiences higher voltage gradients across its body, galvanotaxis aligns the fish so that it swims toward the anode until the voltage is strong enough to induce narcosis, a sleeplike state (Sternin et al. 1972). In efficient electrofishing operations, narcosis occurs within a meter or less of the anode, where fish can be netted easily. Increasing voltage gradients beyond that needed for narcosis lead to tetany: muscle rigidity and seizures that cause the fish to quiver (pseudo-forced swimming) (Vibert 1967).

Immediate fish death resulting from DC electrofishing is uncommon (Pratt 1954; Bouck and Ball 1966); however, physical injury and physiological trauma not readily apparent from cursory external examination are known to occur (Mc-

Crimmon and Bidgood 1965; Horak and Klein 1967; Sharber and Carothers 1988a; Holmes et al. 1990).

Sharber and Carothers (1988a) reported that 43–67% of rainbow trout *Oncorhynchus mykiss* (≥300 mm total length) captured by pulsed DC electrofishing equipment suffered spinal compression fractures, and that electrical pulse shape significantly influenced the frequency of injury. Most injuries occurred with the quarter-sine wave (67%) and fewest with the exponential and square-wave pulses (43% each). Reynolds and Kolz (1988) suggested subsequently that rainbow trout may have a relatively low threshold for reactions to electrical stimulation and that most electrofishing equipment is operated at energy levels at or above that threshold. They concluded that the electric field used by Sharber and Carothers (1988a) was stronger than necessary for efficient electrofishing in the circumstances of the experiments reported and that the observed injuries were an inevitable result.

Reynolds and Kolz's conclusions are consistent with the standard paradigm of electrofishing theory, which hypothesizes that injury to fish occurs as a result of severe muscular contractions during tetany (Cowx and Lamarque 1990). Because tetany is associated with shock near the electrode in the strongest part of the electric field, the hypothesis assumes that the principal cause of morphological damage is high voltage gradient around the fish. This hypothesis has led to the widely held opinion that vertebral fracturing can be avoided if electrofishing equipment is operated at voltage levels sufficiently strong to induce narcosis but weak enough to avoid tetany (Vibert 1967; Sternin et al. 1972; Novotny and Priegel 1974).

The standard paradigm and its concurrent assumptions were challenged by Sharber and Carothers (1988b), who described preliminary data that indicated spinal injuries often occur at voltage gradients below that required to produce narcosis, and therefore below that associated with the onset of tetany.

The experiments reported and discussed here were designed to identify characteristics of pulsed DC responsible for incidence of spinal injury in rainbow trout. Specifically, we (1) tested the hypothesis that incidence of spinal injury is primarily due to the steep gradient of voltage encountered by fish near the anode, (2) compared incidence of injury among four pulse frequencies and a complex pulse pattern, and (3) tested the electrofishing efficiency of the complex pattern.

Methods

Field experiments were conducted in the Colorado River between Glen Canyon Dam and Lees Ferry, Arizona, during seven sampling efforts between 1988 and 1991. Because of the hypolimnetic water releases from the dam, water temperature remained between 9 and 11°C throughout the period of experiments. Conductivity ranged from 600 to 800 μS/cm, and water depth at sample locations ranged from 1 to 3 m. In this reach of the Colorado River, below the dam and above sediment-introducing tributaries, the water runs clear.

We electrofished at night with a brightly illuminated work area extending 5 m from the anode. The distance between anode and cathode was approximately 8 m. Prior to field trials, the output voltage and current meters of each pulsator were calibrated with an oscilloscope. The voltages used in the field were those required to deliver about 12 A (peak value) of electric current between electrodes. In our experience on this river, 12 A is the minimum current observed to induce good electrotaxis beginning 3–5 m from the anode and narcosis within approximately 1 m of the anode. During the trials, we moved the electrofishing boat several hundred meters between sampling locations to reduce the possibility of reshocking fish.

Data were collected only for rainbow trout 300 mm or more in total length. Captured fish were immediately asphyxiated and stored on ice in the field. Compression fractures of vertebrae were assessed by examining X-ray plates obtained with conventional diagnostic medical techniques (Sharber and Carothers 1988a). Specimens for which X-ray analysis could not be made within a few days of capture were frozen.

In our first series of experiments we tested the hypothesis that incidence of spinal injury is primarily due to the steep gradient of voltage encountered by fish near the anode. Fish were exposed to one of three voltage gradients produced by different anode systems: (1) a 1-m-diameter stainless steel ring with 10 droppers of stainless steel cable 1 cm × 20 cm (Novotny 1990), (2) a 30-cm-diameter stainless steel sphere, and (3) a 1.2-m × 1-cm stainless steel cable.

We did not map the precise distribution of the electric field for each of the electrodes with the boat and anode in a stationary and stable position. In the dynamic conditions under which we chose to conduct the tests, the boat was continuously moving and turning in a wide variety of habitats, substrate conditions, and water depths. The anode

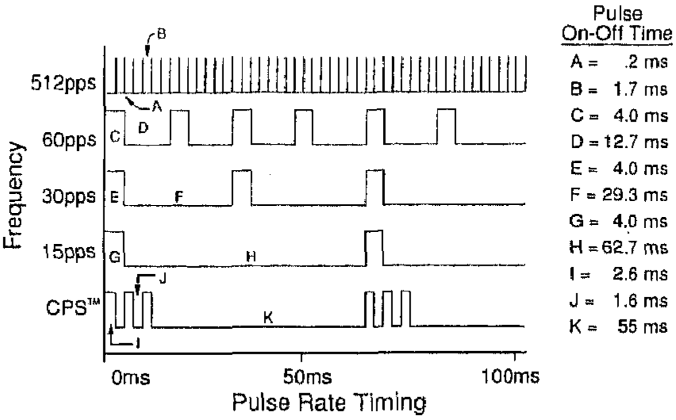

FIGURE 1.—Pulse shape, rate, and repetition pattern for four experimental electroshocking frequencies and the complex pulse pattern.

was swung from a cable 2 m in front of the boat and constantly changed its position relative to the cathode. Fish approached the anode from random depths and directions. These conditions, which are encountered in all electrofishing operations, negate any voltage gradient map derived from measurements under static conditions. We assumed that our sample size would be sufficiently large to average out the variables well enough to show the effect of the different field intensities near the electrodes where the most intense gradients exist.

This methodology was based on a fundamental principle of electric field theory: patterns of distribution of the voltage gradient within a few multiples of the principal dimension of an electrode are determined by the shape and size of the electrode (Feynman et al. 1964; Sternin et al. 1972; Novotny and Priegel 1974). For electrodes carrying the same amperage, the current in the surrounding water will necessarily be more dense if the electrode is small than if it is large. Ohm's law ($E = IR$) says that the voltage gradient (E) across a water column (R) of unit size through which the electric current (I) is passing changes linearly with amperage. The precise voltage gradient that a fish encounters when approaching the anode cannot be determined under dynamic field conditions, but first principles of physics show that the gradient increases rapidly near the electrode.

If anodes of significantly different size but carrying the same amperage are used, the standard paradigm predicts that more injuries would be recorded for fish captured with the small electrode than with the large one due to the much higher voltages that exist around the small one. In our experiment, therefore, the voltage gradient near the anode was least for the droppers suspended from the 1-m ring, intermediate for the 30-cm sphere, and greatest for the 1.2-m cable (Novotny 1990).

To maintain a constant 12-A output, we applied 215 V to the dropper ring, 315 V to the sphere, and 380 V to the cable. Higher voltages used for the sphere and cable were necessitated by the larger electric resistances that these smaller electrodes offered to electric current flow (Novotny and Priegel 1974).

The ring anode was operated just above the surface with only the droppers submerged, the sphere anode was submerged to a depth of approximately 25 cm, and the cable anode was suspended vertically to a maximum depth of about 1.2 m. Pulsed DC was supplied through a Coffelt VVP-15 electrofisher at 60 Hz (pulses per second, pps) and a pulse width of 4 ms. The cathode used was always a 30-cm stainless steel sphere suspended from the stern of the boat and submerged to a depth of about 25 cm.

In our second series of experiments we compared incidence of injury among four pulse frequencies (15, 30, 60, and 512 pps) and a complex pulse frequency pattern. The experiments were designed to quantify the anticipated relationship between increasing pulse rate and increase in trauma. Both electrodes were 30-cm-diameter stainless steel spheres submerged to a depth of about 25 cm. A Coffelt VVP-15 delivered 15, 30, and 60 pps, each square wave with a duration of 4 ms. A Coffelt C-850 generated square waves at 512 pps with a 0.2-ms pulse width, and a Coffelt Mark XXII provided the complex pulse system (CPS®). Figure 1 shows the pulse patterns generated by these systems.

The complex pattern was composed of high-frequency (240 pps) bursts of three square-wave pulses 2.6 ms in width separated by approximately 1.6 ms; the three-pulse bursts were repeated 15 times per second. We used an electronic pulsator that could generate square waves of two frequencies simultaneously: 15 pps and 240 pps. The low-frequency generator acted as a switch, turning the high-frequency oscillator on and off 15 times per second. The pulse widths were chosen to allow three of the high-frequency pulses to be delivered to the electrodes in brief "packets" having a total width off about 11.0 ms. The high-frequency oscillator was then off for about 55 ms before the next packet of three high-frequency pulses was generated.

The third series of experiments was designed to compare the relative electrotaxis efficiency of the complex pulse pattern with those of two commonly used pulse frequencies, 30 and 60 pps.

TABLE 1.—Frequency of spinal injuries sustained by rainbow trout (≥300 mm total length) during electrofishing as a function of electric fields induced by three types of anodes.

Electrode shape	Sample size	Injured fish	
		Number	%
Sphere	116	50	43
Cable	23	15	65
Ring	60	26	43

Hatchery-reared rainbow trout (250–300 mm total length) were subjected to electric current in a concrete raceway. Conductivity of raceway water was 450 μS/cm, and temperature was 18°C. Two stainless steel, 30-cm spherical electrodes were placed 14 m apart along the longitudinal midline of the raceway. A 1 × 3-m cage made of lumber and burlap cloth was set across the raceway midway between the anode and cathode. The electrodes were energized by the appropriate pulsators, as described above, for delivering the desired pulses.

During the trials, two observers were stationed near the anode, one on either side of the raceway. A third person operated the pulsators and timed each event with a stopwatch. A fourth person moved rainbow trout from an isolated holding pen to the cage for each experimental cycle. For each test the pulsator was set with the voltage control at 0. A fish was then moved from the holding pen into the cage and allowed up to 2 min to return to normal activity. The voltage was then increased until the fish became active and moved rapidly about the cage. At this point, the cage was opened toward the anode, allowing the fish to begin electrotaxis toward that electrode. The time between opening of the cage to point of narcosis (when the fish rolled on its side and became relatively motionless) was recorded.

Results

In the experiments designed to test injury rate in relation to voltage gradients, high incidence of spinal injury (43–65%) was observed with all three anodes. The lower, nearly identical, injury rates (43%) occurred with the sphere and ring anodes. The higher rate (65%) occurred with the cable anode (Table 1).

In the second set of experiments, the incidence of spinal injury (3%, 24%, 43%, 62%) increased with pulse frequency (15, 30, 60, and 512 pps, respectively; Figure 2). The relationship appears to be curvilinear. In two trials, the complex pulse pattern injured 7 and 9% of the specimens examined (overall, 8%: Figure 2).

Injuries observed in both the first and second sets of experiments consisted of spinal compression fractures detected by X rays (Figure 3).

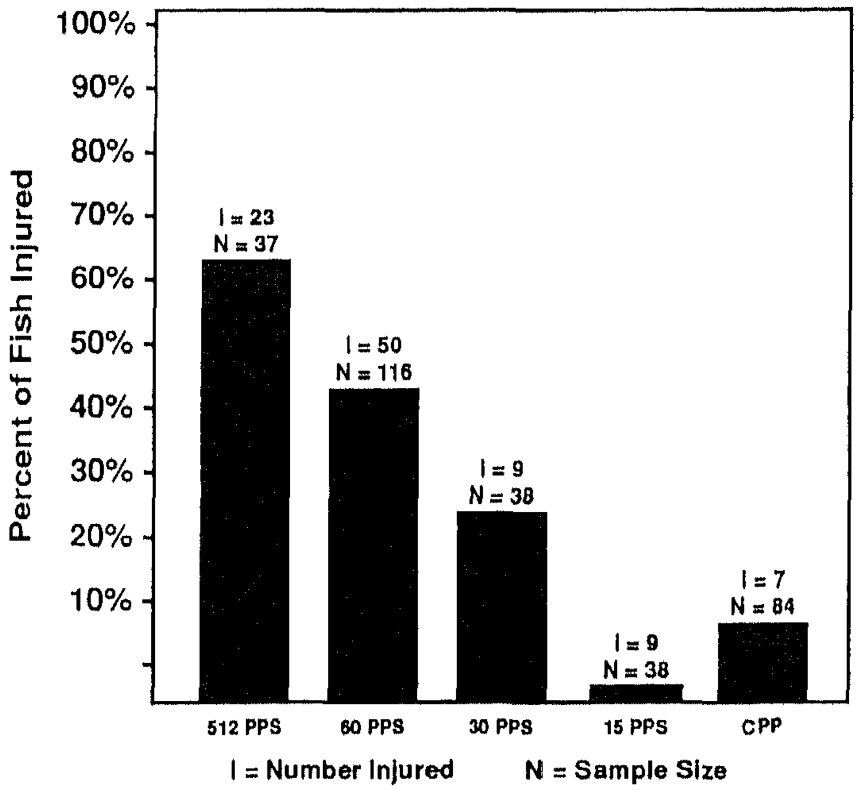

FIGURE 2.—Electroshocking injury of rainbow trout in relation to pulse frequency (CPP is complex pulse pattern).

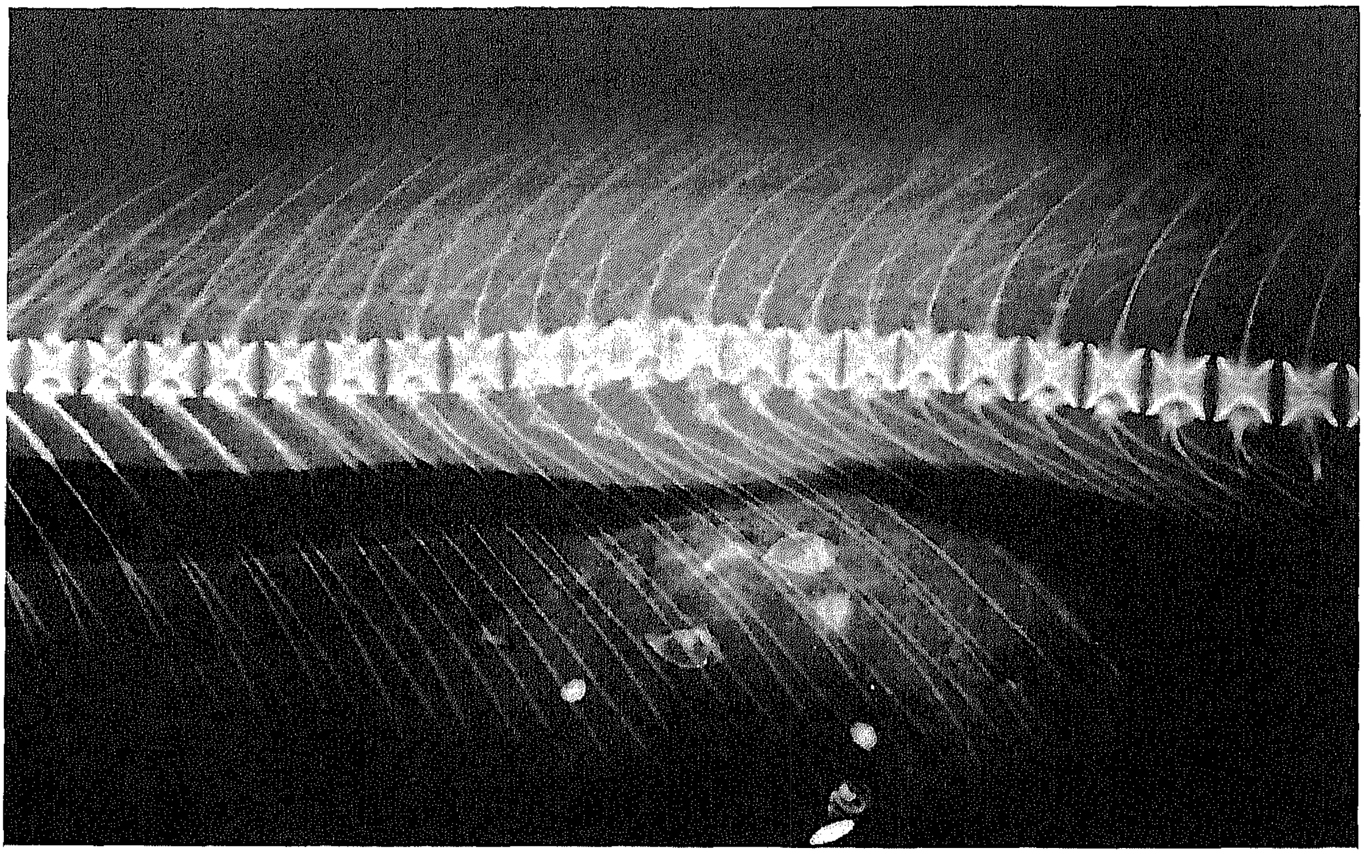

FIGURE 3.—X ray of a rainbow trout showing compressed and fractured vertebrae (near center of photograph). Note detached small bones at site of injury.

In the raceway experiment, no difference between pulse types was observed in the mean time it took fish to reach the anode: 60 pps, 28 s (SE = 3.4, $N = 16$); 30 pps, 27 s (SE = 5.1, $N = 16$); complex pattern, 26 s (SE = 2.5, $N = 13$).

Discussion

The prevailing paradigm in the field of electrofishing predicts that high voltage gradients at the anode are the principal cause of morphological damage to shocked fish. If this were correct, the incidence of injury in our experiments should have been lowest with the droppers suspended from the 1-m ring, intermediate with the 30-cm sphere, and highest with the 1.2-m cable. However, our results demonstrated no consistent relationship between voltage gradient and incidence of spinal injury. Two of the electrodes, the 1-m dropper ring and the 30-cm spherical anode, caused almost identical rates of spinal injury in captured fish, although principles of physics indicate these two electrodes had different average current densities and voltage gradients near their surfaces.

The 1.2-m cable electrode produced the highest voltage gradient and the highest injury rate, which seems to support the voltage gradient–injury hypothesis. However, fish captured with the cable were exposed to electric shock for a longer time than were those captured by the other two methods. This difference occurred because the dropper ring and spherical electrodes functioned at the water surface, where fish could be easily and quickly removed from the electric field, whereas the cable electrode hung a meter below the surface and the fish were more difficult to net from the field. Duration of electric stimulus is a recognized factor in trauma to nerves (Best and Taylor 1950); therefore, prolonged exposure rather than greater voltage gradient may have been responsible for the higher cable-related injury rate. More investigation is warranted.

Our failure to find a relationship between voltage gradient and injury rate with two of the three anodes challenges the assumption that tetany induced by high voltage gradients is the primary cause of spinal injuries in shocked fish. Furthermore, in the studies reported here and by Sharber and Carothers (1988a), few if any of our specimens exhibited symptoms of tetany despite the high incidences of injury.

In contrast to the results of the voltage gradient experiments, the pulse frequency experiments demonstrated a curvilinear relationship with injury. The highest pulse frequencies were associated with the highest incidence of spinal injuries.

Our data support Vibert's (1967) recommendation that low frequencies be used to reduce the chance of injuring fish, and they contradict Lamarque's (1990) suggestion that narrow, high-frequency pulses should produce a low injury rate. Lamarque recommended a frequency near 500 pps with pulse widths of 0.2 ms, but our use of 512 pps at 0.2 ms produced the highest rate of injury observed.

Results of our experiments suggest that moderate to high pulse frequencies rather than high voltage gradients are the primary cause of spinal injury. We further suggest that (1) electrofishing-induced seizures capable of causing spinal compression fractures can happen any time after electrotaxis begins, (2) the state of tetany need not be reached, and (3) injury-causing seizures are relatively independent of the strength of the electrical stimulus.

These propositions rest on our belief that electrofishing-induced spinal injuries are the result of myoclonic jerks of the white muscle tissue on either side of the spine that occur during the epileptic seizures of electrotaxis and narcosis (Penfield and Jasper 1954). Myoclonic jerks are the simultaneous contraction of parallel muscle myotomes that frequently accompany the onset of epileptic events. Epileptic events, in turn, describe the physiological response of animals, even at the tissue and cellular levels, to chemical, electrical, or other shocks to the central nervous system (Delgado-Escueta et al. 1986). When the central nervous system is overwhelmed by the stimulus, seizures occur (Penfield and Jasper 1954). During seizures, vertebral damage caused by myoclonic jerks of muscles paralleling the spine is common in humans and in other vertebrates (Fink 1979). We believe that more fish injuries are seen at higher pulse frequencies because the trauma of myoclonic jerks in white muscles does not develop to the point of an epileptic seizure as rapidly at low frequencies as at higher frequencies.

The complex pulse pattern—three high-frequency pulses (240 pps) and an interval of 55 ms before the next pulse packet—caused relatively few injuries despite the high pulse frequency. It seems reasonable to infer that reducing the total amount of electricity per unit of time lessens the severity of myoclonic jerks. The reduction in amount of electricity did not compromise electrotaxis efficiency, which was comparable to that produced by 30 and 60 pps. This, in turn, suggests that the strong automatism of electrotaxis does not determine the intensity of myoclonic jerks.

We believe that this is the first paper to associate the phenomena of electrofishing with the well-known epilepsies seen in higher vertebrates. The hypothesis is testable because specific changes in brain activities are characteristic and diagnostic of epilepsy (Best and Taylor 1950; Brazier 1973; Engel 1989).

Our work has been confined to rainbow trout, which, as postulated by Reynolds and Kolz (1988), are highly susceptible to injury during electrofishing. Our experiments have demonstrated, however, that it is practical to build equipment for electrofishing that can catch fish as efficiently as can standard models and also reduce the incidence of spinal injury.

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