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Effect of Electrofishing Pulse Shape and Electrofishing-Induced Spinal Injury on Long-Term Growth and Survival of Wild Rainbow Trout

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Abstract.—High rates of spinal injury from electrofishing have been reported for rainbow trout *Oncorhynchus mykiss*, but little is known about the fate and performance of injured fish. We conducted a long-term experiment to evaluate how incidence and severity of electrofishing-induced spinal injury affects growth and survival. We electroshocked 866 wild rainbow trout from the Gallatin River, Montana, using one of three different DC pulse shapes (smooth, half pulse, and full pulse), X-rayed the fish to determine degree of spinal injury, and compared short-term (100-d) growth and long-term (335-d) growth and survival after transplanting the fish to a 0.6-ha pond (stocking biomass, 255 kg/ha). Rainbow trout shocked with pulsed DC had significantly higher ($P = 0.0001$) incidence (40–54%) of spinal injury than those shocked with smooth DC (12%); injuries were also more severe among fish captured with pulsed DC ($P < 0.01$). Incidence and severity of injury were positively correlated with fish length ($r = 0.79$–0.83, $P < 0.02$). Few surviving fish (7 of 418) at the end of the study exhibited outwardly visible spinal deformities. Healing of spinal injuries was readily apparent on radiographs as evidenced by calcification and fusion of damaged vertebrae. Long-term survival of rainbow trout was not affected by pulse shape used during capture or by severity of electrofishing-induced injury. However, fish with moderate to severe injury (spinal misalignment and fracture), representing 28% of the total number shocked, had markedly lower growth and condition after 335 d than fish with no or low spinal injury.

Electrofishing has long been viewed as a relatively harmless fish-sampling method when used appropriately. However, recent reports of significant skeletal damage and hemorrhaging from shocking with standard equipment and settings have caused biologists to question the assumption that its effects on fish health are minimal (Snyder 1992, 1995).

Rainbow trout *Oncorhynchus mykiss* appear particularly susceptible to injury during shocking (Reynolds and Kolz 1988; Snyder 1992). Sharber and Carothers (1988) found spinal injuries in 44% to 67% of large (>300 mm fork length) rainbow trout electrofished with pulsed direct current (DC). Wild rainbow trout larger than 400 mm shocked with pulsed DC in Alaska had a 41% spinal injury rate and 14% short-term (96 h) mortality, thus prompting a moratorium on electrofishing in trophy trout waters in the state (Holmes et al. 1990). Of 693 wild rainbow trout shocked in Montana rivers (201–554 mm), 50–70% sustained spinal injury resulting in 769 hemorrhages and 2,647 injured vertebrae (Fredenberg 1992). Pulse shape and frequency are among the variables that influence incidence and severity of injury (Sharber and Carothers 1988; McMichael 1993; Sharber et al. 1994). Lowest injury rates in rainbow trout have been observed with smooth DC and highest rates with pulsed DC at high (≥60 Hz) frequency (Fredenberg 1992; McMichael 1993; Sharber et al. 1994).

Despite reports of high injury rates in rainbow trout and other salmonids, the fate of injured wild fish over the long term and the potential population effects of shocking remain largely unknown (Snyder 1992). Immediate mortality after electrofishing is usually low, and external signs of injury are often absent or undetected (Hudy 1985; McMichael 1993; Hollender and Carline 1994; Sharber et al. 1994; but see Hauck 1949; Holmes et al. 1990). Some investigators have inferred that injuries often heal and long-term mortality is low,

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but pronounced spinal deformities after electrofishing have been reported in other studies (see Snyder 1992). To date, most studies that have examined effects of electrofishing on growth and survival in trout (Hudy 1985; Gatz et al. 1986; Taube 1992; McMichael 1993; Dwyer and White 1995) have been conducted over short time intervals (<35 d) with hatchery fish (e.g., Hudy 1985; McMichael 1993; Dwyer and White 1995; but see Gatz et al. 1986), and, except for the study by Taube (1992), they have not distinguished between injured and uninjured fish. Our study was designed to (1) characterize short-term (100-d) growth and long-term (335-d) growth and survival of wild rainbow trout shocked with one of three DC pulse shapes (smooth, half pulse, and full pulse); (2) compare growth and survival of injured and uninjured shocked fish in the field; and (3) evaluate healing of electrofishing-induced spinal injuries.

Methods

Experimental site.—Growth and survival of electroshocked rainbow trout were evaluated in an irrigation storage pond on the Montana State University campus. The 0.6-ha pond had a maximum depth of 4.5 m, mean depth of 3.5 m, and a uniform mud and gravel bottom. Summer water temperatures were typically less than 20°C (range, 10–26°C) and ranged between 1.2 and 5°C in winter. Dissolved oxygen concentration ranged from 8.0 to 11.5 mg/L. Inflow to the pond was by diversion from a nearby creek and outflow was through an irrigation pump. Fish movement in and out of the pond was prevented by screened inflow and outflow pipes. Qualitative plankton tows in the pond showed that abundant trout food—*Gammarus*, *Daphnia*, and *Diaptomus*—was present. Before fish introduction, a few ($N = 16$) brook trout *Salvelinus fontinalis* were removed with gill nets. No other fish species were present. A 3-m-high fence surrounding the pond prevented angler access.

Fish collection.—Wild rainbow trout were collected from a 14-km reach of the Gallatin River downstream from Big Sky, Montana, on July 27 and 28, 1992, at water temperatures between 13 and 16°C and conductivity of 260 μS/cm. Fish in this section had a low likelihood of previous exposure to electroshock. Limited shocking had occurred in the upper 6 km of the section in 1989, and the last extensive population estimate was in 1984. Fish were captured by single-pass electrofishing from a 3.8-m fiberglass drift boat equipped with a 3,000-W, 220-V AC generator, a locally manufactured electrofisher, and a mobile electrode system (Vincent 1971). The anode was a 25.4-cm aluminum triangle attached to electrical cable, and the cathode was a 1.2-m^2 stainless steel plate attached to the boat. The DC voltages (rectified AC) were adjusted to provide 3 A of current, a level used in normal electrofishing operations in the region to produce electrotaxis and high capture efficiency of trout (Fredenberg 1992). A portable oscilloscope was used to measure output voltage and the voltage gradient (V/cm) surrounding the anode in the field. Voltages varied from 350 to 400 V for smooth DC, from 200 to 400 for half-pulse DC, and from 0 to 400 V for full-pulse DC (Figure 1). Pulsed DC was delivered as a half-sine wave at a frequency of 60 Hz. Voltage gradients are shown in Figure 2.

The three DC pulse shapes were used sequentially (smooth, half pulse, and full pulse) until about 330 fish had been collected for each pulse shape test group. Only one pulse shape was used at a time, and a section 100–1,000 m long separated reaches shocked with different pulse shapes to ensure that fish were shocked with only one pulse shape. Fish were held in live wells on the electrofishing boat, then transported in oxygenated tanks to separate outdoor hatchery raceways at the Bozeman Fish Technology Center. After 24 h, fish from each test group were moved to indoor tanks for processing. Fish were anesthetized with MS-222 (tricaine methanesulfonate), measured for fork length, weighed, and tagged with both an uncoded wire tag in the snout or base of left pelvic fin or dorsal fin to identify pulse shape test group and an uniquely coded visible implant (VI) tag in the postorbital adipose tissue for individual identification. Fish were X-rayed (right lateral view) in groups of 10 with a Minxray X750G portable X-ray machine with Konica Blue film exposed for 0.6–0.8 s at 50 kV and a source-to-image distance of 760 mm. Trout ranged from 153 to 388 mm fork length. Length distributions (mean ± SE) of fish were similar among the three test groups: smooth = 252.6 ± 16.3 mm; half pulse = 244.5 ± 2.4 mm; and full pulse = 245.4 ± 16.3 mm (Kolmogorov–Smirnov test, Zar 1984; $D = 0.22–0.33$, $P > 0.6$).

Survival and growth.—After processing, 866 fish (smooth DC, $N = 241$; half-pulse DC, $N = 309$; full-pulse DC, $N = 316$) were transported from the hatchery to the pond and released, 1–3 d after collection, on July 29–30, 1992, at an initial stocking biomass of 255 kg/ha. Fewer fish from the smooth DC test group were released because some had escaped from the outdoor raceway. The

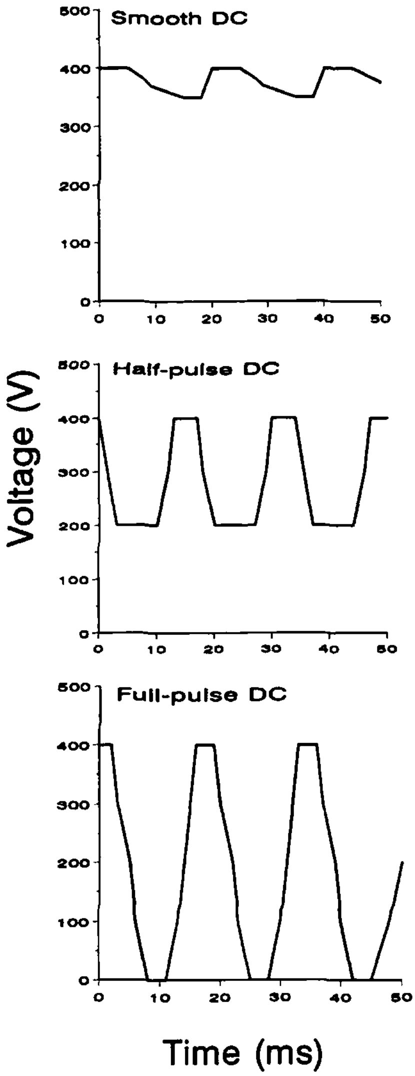

FIGURE 1.—Electrical pulse shapes (measured by oscilloscope) generated by electrofisher at smooth, half-pulse, and full-pulse DC settings.

pond was visually inspected for dead fish twice daily for 3 months postrelease and three to five times a week thereafter during ice-free periods.

To measure short-term growth among test groups, we removed about 10% of the fish stocked from each group at 100 d postrelease (7 November) using fyke nets and short-term gill-net sets. Sampled fish were weighed, measured, and identified by tag. Changes in length, weight, and condition ($K = 10^5 \times$ [weight, g]/[length, mm]^3) were determined for fish that retained the VI tag.

To assess long-term survival and growth, we removed all remaining fish from the pond by treating it with 5% liquid rotenone on July 1, 1993 (335 d postrelease). Rotenone was uniformly distributed via a drip hose placed in the propeller wash of an outboard motor. Most mortality occurred within 3 d, but we continued monitoring the pond for 7 d after application. We believe total removal was achieved because surface feeding by trout, commonly seen before application, was not observed for 1 week after application. The collected fish were weighed, measured, and identified by tag. Long-term survival (S) was determined by $S = I - R + G$, where I was the number introduced, R the number removed from the pond at the end of the study, and G the number removed to assess short-term growth.

We used a log-likelihood contingency analysis (G-test, Zar 1984) to compare long-term survival among the three pulse-shape groups. Short-term and long-term changes in growth and condition were compared among pulse-shape groups by analysis of variance (ANOVA) and Tukey's multiple comparison test (Zar 1984). Following Trippel and Hubert (1990), we used analysis of covariance to adjust for effects of fish length on growth.

Spinal injury.—We assessed spinal injury by rating incidence and severity of injury according to criteria proposed by J. Reynolds (Alaska Cooperative Fish and Wildlife Research Unit, personal communication; see also Hollender and Carline 1994) (Table 1). For each fish, the rating for the most serious injury observed was designated as the overall injury rating. X-ray plates from different treatments were shuffled and read randomly to eliminate bias. Spinal abnormalities present before electroshocking were readily distinguished from recent injury by the evidence of calcification (Sharber and Carothers 1988; Fredenberg 1992), and these were eliminated from our injury rating; such abnormalities were present in only 1% of fish X-rayed. We assessed healing of spinal injury at the end of the study by X-raying 38 randomly selected fish having various degrees of initial spinal injury and rating the X-rays of these fish without knowledge of initial injury. We then determined degree of healing by comparing initial and final X-rays.

We compared incidence and severity of spinal injury among pulse-shape treatment groups with a G-test. Effects of injury severity on growth and condition were analyzed by ANOVA. Associations between fish length and injury severity were assessed by simple linear correlation (Zar 1984).

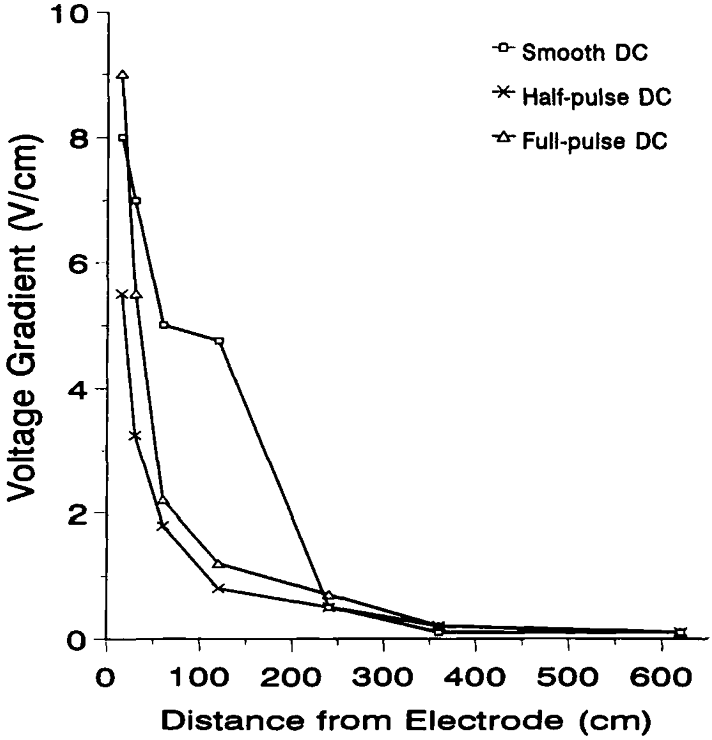

FIGURE 2.—Peak voltage gradients (V/cm; measured by oscilloscope) surrounding the anode for the three DC pulse shapes used in the study.

Results

Spinal Injury

X-rays were of good quality with greater than 99% of the 866 readable. Initial spinal injury differed significantly among the three pulse-shape groups in both incidence (Table 2; $G = 115.7$, $P = 0.0001$) and severity ($G = 49.8$, $P = 0.0001$). Rainbow trout shocked with half-pulse (HP) and full-pulse (FP) DC waveforms had about three to four times higher proportion of spinal injuries than those shocked with smooth (SM) DC (HP, 40%; FP, 54%, SM, 12%). A significantly higher proportion of class 1 and 2 injuries ($P < 0.01$) occurred in the HP and FP groups than in the SM group. Similarly, fish in the FP group had a significantly higher proportion of class 1 and 2 injuries ($P < 0.05$) than did the HP group. However, the proportion of fish with the most severe injury (class 3) did not differ significantly among pulse-shape groups ($P = 0.13$); injury ranged from 6% in SM and HP groups to 10% in the FP group (Table 2). Overall, 9% of rainbow trout shocked sustained class 1 injury, 20% class 2, and 8% class 3.

TABLE 1.—Criteria used to rate severity of electrofishing injury to rainbow trout. Injuries were determined from examination of radiographs.

Injury class	Spinal damage
0	None apparent
1	Compression of vertebrae
2	Misalignment and compression of vertebrae
3	Fracture of one or more vertebrae or complete separation of two or more vertebrae

Incidence and severity of injury varied with fish length (Figure 3). The overall incidence of injury was positively correlated with fish length ($r = 0.83$, $P = 0.01$). The proportion of fish with class 3 injury also was positively correlated with length ($r = 0.79$, $P = 0.02$), whereas the proportion of fish with class 1 injury was negatively correlated with length ($r = -0.92$, $P < 0.001$). The proportion of rainbow trout with class 2 injury showed no significant association with length across all length classes ($r = 0.46$, $P = 0.9$); however, proportion of class 2 injury was positively correlated with length for fish less than 250 mm ($r = 0.98$, $P = 0.02$).

Of 418 fish captured at the end of the study, we

TABLE 2.—Incidence and severity of spinal injury in rainbow trout collected by electrofisher from the Gallatin River, Montana. Three DC pulse shapes were used. Number and percentage (in parentheses) of fish in each injury class (Table 1) for each pulse-shape group are shown for all fish at the beginning of the study and for all fish individually identifiable (i.e., retained VI tag) at the end of the study (335 d).

	Beginning					End				
		Number (%) by injury class:					Number (%) by injury class:			
Waveform	*N*	0	1	2	3	*N*	0	1	2	3
Smooth DC	241	212 (88)	5 (2)	9 (4)	15 (6)	54	47 (87)	1 (2)	3 (5.5)	3 (5.5)
Half-pulse DC	309	186 (60)	31 (10)	74 (24)	18 (6)	57	35 (61)	7 (12)	14 (25)	1 (2)
Full-pulse DC	316	145 (46)	44 (14)	95 (30)	32 (10)	103	48 (47)	17 (16)	28 (27)	10 (10)

observed outwardly visible spinal deformities in 0 SM, 2 HP, and 5 FP fish. Healing (calcification) of injured vertebrae was readily apparent from radiographs taken from the 38 injured fish chosen at random and X-rayed at the end of the study. Calcification made judging severity of initial injury difficult but also made spinal damage from electroshocking more visible. Damaged vertebrae, particularly those with hairline fractures (class 3), were not always detected in initial radiographs. The proportion of fish with class 3 injury increased from 16 to 68% (Table 3). Proportions of fish classified in each injury class at the beginning and end of the study were significantly different ($P < 0.001$). For the 38 fish examined, the spinal injury rating increased in severity for 60%, remained unchanged for 34%, and decreased for 5%.

Survival

During the period of electroshocking, transferring to the hatchery holding facility, X-raying, and transporting to the pond, only 1 fish (in the HP

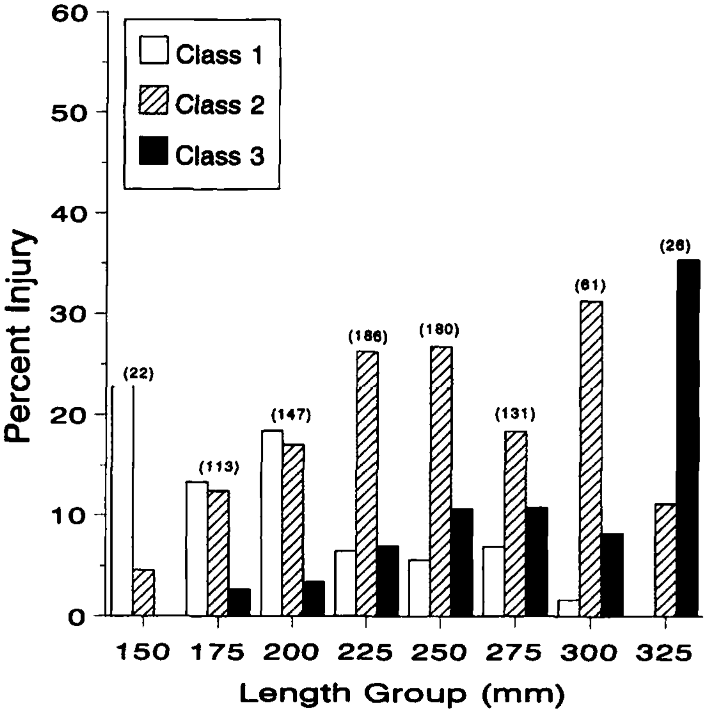

FIGURE 3.—Severity of spinal injury in rainbow trout by length-group ($N = 866$). Values form the lower bounds of each 25-mm length-group. The sample size for each group is shown in parentheses.

TABLE 3.—Spinal injury rating of 38 injured rainbow trout X-rayed at the beginning and end (335 d) of the study. The number and proportion (in parentheses) of fish are shown for each injury class.

Study time	Number (%) by injury class		
	1	2	3
Beginning	8	24	6
	(21)	(63)	(16)
End	0	12	26
	(0)	(32)	(68)

group) died. Of the 866 fish stocked in the pond, 115 were removed for the short-term growth and condition assessment, 21 were recovered as dead fish, and 418 were recovered after the rotenone treatment; the unaccounted for 312 fish were considered in situ mortalities because screening on inflow and outflow pipes prevented fish emigration from the pond.

Short-term mortality (7 d postrelease) was low among all test groups (FP = 1, HP = 2, and SM = 12). The higher short-term mortality in SM group fish was probably due to the increased stress incurred when escaped fish were recaptured from the outdoor raceway. Of the 21 dead fish recovered from the pond during the study, 15 (71%) were recovered within the first week following introduction.

Long-term survival (335 d) was similar among all pulse-shape groups (SM = 54%, HP = 58%, FP = 60%; $G = 0.3$, $P = 0.8$). Injury severity also had no apparent influence on long-term survival. Among the survivors that retained the VI tag (215 or 51%), the proportions in each injury class were similar within each pulse-shape group at the beginning and end of the study (Table 2; $G = 0.3$–0.5, $P = 0.5$–0.9). The overall proportion of injured and uninjured fish within each pulse-shape group at the beginning and end of the study was also similar ($G = 0.02$–0.5, $P = 0.8$–0.9).

Growth

Measurement of short-term growth and condition change was limited to 62 fish or 54% of the sample ($N = 115$) because the remainder had lost the VI tag. Average changes in length, weight, and condition over this period were not significantly different among the three pulse-shape groups (Table 4). Fish from all three waveform groups lost condition. In contrast, change in length, weight, and condition showed significant differences among injury classes, although comparisons were based on small sample sizes for injury classes 1 and 3. Uninjured (class 0) fish increased significantly more in length (19.5 mm) and weight (28.8 g) than injured fish (means: 6.1 to 11.5 mm, −19.5 to 12.7 g). Condition declined in fish from all injury classes after 100 d, but the decline was significantly greater for injured fish.

Unlike the 100-d comparison, average weight

TABLE 4.—Mean changes in length, weight, and condition[a] of electroshocked rainbow trout after 100 and 335 d classified by DC pulse shape (SM = smooth, HP = half pulse, and FP = full pulse) or severity of spinal injury (Table 1). Standard deviations of means are in parentheses; N is the total number of fish in the sample, and P indicates results of analysis of variance tests. Within pulse-shape and injury class groups, values along a row without a letter in common are significantly different ($P \leq 0.10$).

Variable	Pulse shape				Injury class				
	SM	HP	FP	*P*	0	1	2	3	*P*
Time interval: 100 d									
Length (mm)	17.0 z	7.8 z	14.2 z	0.14	19.5 z	11.5 y	6.1 y	9.3 y	0.003
	(14.2)	(8.0)	(13.2)		(13.4)	(6.5)	(7.4)	(18.3)	
Weight (g)	22.6 z	8.8 z	13.4 z	0.41	28.8 z	12.7 y	1.5 y	−19.5 y	<0.001
	(26.5)	(14.2)	(35.6)		(22.1)	(9.4)	(14.2)	(74.0)	
Condition	−0.03 z	−0.03 z	−0.04 z	0.74	−0.01 z	−0.05 y	−0.06 y	−0.09 x	0.04
	(0.09)	(0.06)	(0.06)		(0.07)	(0.06)	(0.05)	(0.10)	
N	19	13	30		31	8	19	4	
Time interval: 335 d									
Length (mm)	9.4 y	19.9 z	13.2 y	0.01	17.1 z	22.3 z	4.8 y	1.5 y	<0.001
	(16.1)	(22.1)	(17.9)		(19.9)	(19.4)	(12.5)	(9.6)	
Weight (g)	26.6 y	47.7 z	30.2 y	0.03	44.3 z	36.9 z	15.4 y	−4.5 y	<0.001
	(39.8)	(50.3)	(44.4)		(45.3)	(39.6)	(42.9)	(25.4)	
Condition	0.06 z	0.07 z	0.04 z	0.33	0.08 z	0.02 y	0.04 y	−0.04 y	0.001
	(0.11)	(0.12)	(0.14)		(0.11)	(0.11)	(0.16)	(0.10)	
N	54	57	103		130	25	45	15	

[a] Condition = $10^5 \times$ (weight, g)/(length, mm)^3.

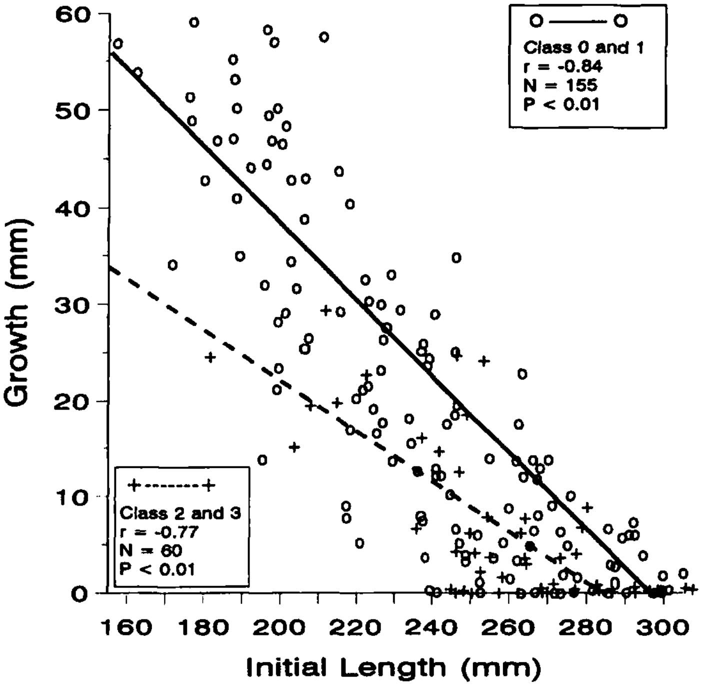

FIGURE 4.—Length–growth regressions for rainbow trout having low (classes 0 and 1) and high (classes 2 and 3) electrofishing injury.

and length changes differed among pulse-shape groups at the end of the study (335 d; Table 4). Average weight gain of HP group fish (47.7 g) was significantly greater than SM (26.6 g) and FP (30.2 g) fish. The HP fish also had significantly greater mean length increase (19.9 mm) than SM fish (9.4 mm) and FP fish (13.2 mm). Condition factor changes were similar among pulse-shape groups, with all groups showing an increase in condition, unlike the decrease observed at 100 d.

Long-term growth and condition differed markedly with degree of injury. Classes 0 and 1 fish gained an average of 36.9 to 44.3 g over the 335-d period, compared to an average loss of 4.5 g for class 3 fish (Table 4). The mean weight gain of classes 0 and 1 fish was more than twice that of fish with class 2 injuries (15.4 g). Mean condition change of class 0 (uninjured) fish was significantly greater than that of injured fish (classes 1, 2, and 3). Condition increased in class 0, 1, and 2 fish but declined in class 3 fish.

Fish with no or low injury grew 5–10 times more in length (means, class 0 = 17.1, class 1 = 22.3 mm) than fish with moderate to severe injury (means, class 2 = 4.8, class 3 = 1.5 mm) (Table 4). Although growth was negatively correlated with initial length for both groups, length–growth regression lines for the two groups also were significantly different (Figure 4; analysis of covariance; t = 2.7, P = 0.01 for slope). The adjusted mean length gain for fish with no or low injury (17.1 mm) was nearly 2.5 times greater than the adjusted mean length gain of fish with moderate to high injury (7.1 mm).

Discussion

Spinal Injury

Overall, 37% (322 of 866) of rainbow trout captured in our study sustained spinal injury during electroshocking. This proportion is comparable to the incidences of electrofishing-induced injury among wild rainbow trout reported by Sharber and Carothers (1988), Holmes et al. (1990), Fredenberg (1992), and Sharber et al. (1994). In their summary of electrofishing injury studies, Hollender and Carline (1994) reported that an average of 33% of wild trout sustained spinal injury during shocking. These studies encompassed a wide range of electrofishing equipment, settings, and environmental conditions.

Pulsed-DC waveforms caused three to four times higher incidence of injury to rainbow trout than did smooth DC in our study. A strong positive relation between injury rate and pulse frequency has been observed consistently in studies of electrofishing injury (Sharber and Carothers 1988; Fredenberg 1992; McMichael 1993; Sharber et al. 1994). Type of pulse shape used in our study also affected severity of injury. Rainbow trout shocked with half-pulse and full-pulse DC had a significantly greater proportion of spinal compression (class 1 injury) and spinal misalignment (class 2 injury) than those shocked with smooth DC (Table 2). In contrast, the proportion of spinal fracture (class 3 injury) was relatively constant (6–10%) among the three pulse-shape groups. Similar levels of class 3 injury (5–10%) among different pulse shapes were also noted by Fredenberg (1992) and Hollender and Carline (1994). The causes for this consistent level of class 3 injury during electroshocking need further investigation. Reynolds and Kolz (1988) suggested that rainbow trout are severely injured when fish are shocked within the area of high voltage that occurs near the anode at all waveforms (Figure 2). Alternatively, Sharber et al. (1994) postulated that "injury-causing seizures are relatively independent of the strength of the electrical stimulus" and are more a function of duration of exposure.

Our findings support earlier work demonstrating a positive relation between fish size and frequency of electrofishing injury (Lamarque 1990; Hollender and Carline 1994). For example, we found that about 40% of trout longer than 200 mm sustained injury compared to about 27% in smaller fish (Figure 3). We also found that longer fish sustained more severe injury. Previous studies of electrofishing injury in wild rainbow trout have focused on injury to fish exceeding 300 mm (Sharber and Carothers 1988; Holmes et al. 1990; Sharber et al. 1994). Our study demonstrated that spinal injuries are detectable in wild rainbow trout at least as small as 150 mm, although damage to smaller fish is more difficult to detect (Fredenberg 1992).

Healing of spinal injury was readily apparent in radiographs of injured fish about 1 year after shocking. Injury sites showed significant calcification, including apparent fusion of vertebrae. Very few fish (7 of 418) exhibited outwardly visible spinal deformities. Our comparison of initial and final injury status, though based on a limited number of fish (N = 38), further suggests that incidence and severity of spinal injury from electroshock may be underestimated with standard X-ray equipment. In addition, radiographs do not detect soft tissue damage, which may be more prevalent than damage to the spinal column (Fredenberg 1992; McMichael 1993).

Effects on Survival and Growth

There was no evidence that pulse shape or degree of spinal injury adversely affected long-term survival of wild rainbow trout, despite significant differences in initial injury. Indeed, the proportion of injured fish within each injury category was remarkably similar at the start and end of the study (Table 2). The range of mortality of rainbow trout among pulse-shape groups in our study (40–46%) was comparable to annual mortality of age-2 and older wild rainbow trout in Montana rivers (about 50%; Vincent 1987). Taube (1992) also found no difference in long-term survival (203 d) among injury classes in hatchery rainbow trout after shocking.

Electrofishing injury, however, did have a marked influence on growth. Rainbow trout with moderate and severe spinal injury (classes 2 and 3) showed little or no increase in length and weight over 335 d compared to uninjured or slightly injured fish which averaged a gain of 17.1 to 22.3 mm in length and 36.9 to 44.3 g in weight. Effects were especially pronounced for the most severely injured fish (class 3), which lost weight and condition during the study. Thus, negative effects of electrofishing injury on growth and condition remained for at least 1 year after injury. This contrasts with the rapid recovery, measured in hours or days, from physiological and behavioral effects of electroshock (Horak and Klein 1967; Mesa and Schreck 1989; Mitton and McDonald 1994). We found no evidence for negative effects of electrofishing pulse shape on long-term growth and condition. These findings underscore the need for investigators to consider severity of injury when assessing incidence and effects of electrofishing injury caused by different pulse shapes.

One should interpret our results with several caveats in mind. First, we suspect that in a dynamic stream environment, skeletal damage could possibly have greater negative effects on growth and survival than it did in our study conducted in a relatively benign pond environment, because of higher physiological demands required for capturing food and maintaining position in flowing water (Horak and Klein 1967). Second, because our study lacked an unshocked control group, we were unable to determine the overall effects of electrofishing on survival and growth, and hence could not definitively determine whether potential negative effects from electrofishing were additive or compensatory. This may have been an important limitation because studies have detected significant differences in growth among shocked and unshocked groups of hatchery rainbow trout (Taube 1992; Dwyer and White 1995) and wild brown trout *Salmo trutta* and rainbow trout (Gatz et al. 1986). Obtaining an unshocked control group of wild rainbow trout of a size comparable to that of the shocked test groups was beyond our logistic capabilities. Nonetheless, by classifying fish by injury severity, we could compare survival and growth of uninjured and injured fish.

Management Implications

Our results from the first long-term study of effects of electrofishing-induced injury to wild rainbow trout lend additional support to management recommendations for using smooth DC or low pulse rates to reduce injury during electrofishing, especially among larger fish (Fredenberg 1992; Snyder 1992, 1995; Sharber et al. 1994). Although we found no evidence that severity of injury or electrofishing pulse shapes affected long-term survival, we did find significantly impaired growth in more severely injured fish (class 2 and 3 spinal injuries). The near absence of outward signs of spinal injury reinforces the need for X-ray analysis to properly assess incidence and severity of spinal injury from electrofishing. Even with radiographs, initial estimates of severe injury should be considered conservative. Additional research is needed to characterize the causes of severe injury during electroshocking, develop ways to reduce it, and examine further the fate and performance of injured fish in the field.

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References

Dwyer, W. P., and R. G. White. 1995. Influence of electroshock on short-term growth of adult rainbow trout and juvenile Arctic grayling and cutthroat trout. North American Journal of Fisheries Management 15:148–151.

Fredenberg, W. 1992. Electrofishing-induced spinal injuries caused by field electrofishing surveys in Montana. Montana Fish, Wildlife, and Parks, Report, Helena.

Gatz, A. J., Jr., J. M. Loar, and G. F. Cada. 1986. Effects of repeated electroshocking on instantaneous growth of trout. North American Journal of Fisheries Management 6:176–182.

Hauck, F. R. 1949. Some harmful effects of the electroshocker on large rainbow trout. Transactions of the American Fisheries Society 77:61–64.

Hollender, B. A., and R. F. Carline. 1994. Injury to wild brook trout by backpack electrofishing. North American Journal of Fisheries Management 14: 643–649.

Holmes, R., D. N. McBride, T. Viavant, and J. B. Reynolds. 1990. Electrofishing induced mortality and injury to rainbow trout, Arctic grayling, humpback whitefish, least cisco and northern pike. Alaska Department of Fish and Game, Division of Sport Fish, Fishery Manuscript 90-3, Anchorage.

Horak, D. L., and W. D. Klein. 1967. Influence of capture methods on fishing success, stamina, and mortality of rainbow trout (*Salmo gairdneri*) in Colorado. Transactions of the American Fisheries Society 96:220–222.

Hudy, M. 1985. Rainbow trout and brook trout mortality from high voltage AC electrofishing in a controlled environment. North American Journal of Fisheries Management 5:475–479.

Lamarque, P. 1990. Electrophysiology of fish in electric fields. Pages 4–33 *in* I. G. Cowx and P. Lamarque, editors. Fishing with electricity: applications in freshwater fisheries management. Fishing News Books, Oxford, UK.

McMichael, G. A. 1993. Examination of electrofishing injury and short-term mortality in hatchery rainbow trout. North American Journal of Fisheries Management 13:229–233.

Mesa, M. G., and C. B. Schreck. 1989. Electrofishing mark–recapture and depletion methodologies evoke behavioral and physiological changes in cutthroat trout. Transactions of the American Fisheries Society 118:644–658.

Mitton, C. J. A., and D. G. McDonald. 1994. Effects of electroshock, air exposure, and forced exercise on swim performance in rainbow trout (*Oncorhynchus mykiss*). Canadian Journal of Fisheries and Aquatic Sciences 51:1799–1803.

Reynolds, J. B., and A. L. Kolz. 1988. Electrofishing injury to large rainbow trout. North American Journal of Fisheries Management 8:516–517.

Sharber, N. G., and S. W. Carothers. 1988. Influence of electrofishing pulse shape on spinal injuries in adult rainbow trout. North American Journal of Fisheries Management 8:117–122.

Sharber, N. G., S. W. Carothers, J. P. Sharber, J. C. de Vos, Jr., and D. A. House. 1994. Reducing electrofishing-induced injury of rainbow trout. North

American Journal of Fisheries Management 14: 340–346.

Snyder, D. E. 1992. Impacts of electrofishing on fish. Report of Colorado State University, Larval Fish Laboratory to U.S. Bureau of Reclamation, Salt Lake City, Utah, and Glen Canyon Environmental Studies Team, Flagstaff, Arizona.

Snyder, D. E. 1995. Impacts of electrofishing on fish. Fisheries 20(1):26–27.

Taube, T. T. 1992. Injury, survival, and growth of rainbow trout captured by electrofishing. Master's thesis. University of Alaska, Fairbanks.

Trippel, E. A., and J. J. Hubert. 1990. Common statistical errors in fishery research. Pages 93–102 *in* J. Hunter, editor. Writing for fishery journals. American Fisheries Society, Bethesda, Maryland.

Vincent, E. R. 1971. River electrofishing and fish population estimates. Progressive Fish-Culturist 33: 163–169.

Vincent, E. R. 1987. Effects of stocking catchable-size hatchery rainbow trout on two wild trout species in the Madison River and O'Dell Creek, Montana. North American Journal of Fisheries Management 7:91–105.

Zar, J. R. 1984. Biostatistical analysis, 2nd edition. Prentice-Hall, Englewood Cliffs, New Jersey.