STUDIES ON THRESHOLD CURRENT DENSITIES FOR CONVULSIONS OF FISH USING A SQUARE WAVE STIMULATOR*

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The threshold current densities and voltage tensions (body voltages) between the head and tail for bringing about distinct reactions in *Salmo irideus, Cyprinus Carpio, Tinca tinca, Gasterosteus aculeatus* and *Salmo fario* were studied. In *C. carpio* and *T. tinca*, absolute current densities required decreased with increase in length of fish. Threshold current densities for different reactions of fish increased with rise in water temperature and conductivity of surrounding medium except in case of *T. tinca* where low current densities were sufficient in higher conductivity of water. Impulse D. C. was superior to continuous D. C. Better effect was noticed in fishes in lower current densities when their bodies were parallel to the lines of current conduction.

INTRODUCTION

The present studies were carried out with a high frequency impulse transmitter producing square wave impulses of variable impulse and pause durations in Landesanstalt fur fishcherei, Albaum, West Germany. The instrument produced impulse frequencies of 76 to 88/second with adjustable impulse and pause durations of 4.8 milliseconds to 1.8 secs. Siemen's pantostat 523 used in previous experiments by Biswas (1971) was limited to impulse frequencies of 26 to 48/ second with constant pause duration of 20 milliseconds. In order to produce an anodic effect on the fish, the current pulses must have the proper shape besides the narcotizing impulse threholds,(Kreutzer and Peglow, 1949). Administration of impulses of short duration, similar to those produced by electric fishes (Torpedo, Raja etc) for capturing their prey appeared to have intensive effect on the fish. Leduc (1903) used impulse current of rectangular form with short continuous impulses followed by longer pause on *Phoxinus laevis* in bringing about distinct anodic reactions. The present studies were carried out for determination of threshold current densities in higher impulse frequencies for bringing about convulsions of fishes.

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Materials And Methods

Electrical field was produced in a wooden trough of 200cm x 54cm x 25cm, which served as experimental tank, using two zinc plates of 54cm x 25cm fixed vertically along the breadthwise sides as electrodes. The tank was filled with water to a depth of 10 cm. The electrodes were connected with the out-put terminals of electronic impulse transmitter (Fig 1) through a voltmeter and amperemeter. Power was drawn from 220V A. C. mains. The transmitter produced continuous D. C. and impulse D. C. of different frequencies with variable impulse and pause durations. A voltmeter connected in parallel to the terminals of electrodes indicated potential drops between the electrodes during the experiment. The wave shape of impulse D. C. and the durations of impulse and pause were checked and recorded by a double beam cathode ray oscilloscope. A thermometer, suspended from a clamp recorded the temperature of the water during experiments.

The conductivity and the temperature of water were measured, the former with Siemen's conductivity meter (Biswas loc cit) Fishes of equal size and age groups were used for different sets of experiments. The test fish after being acclimatised for 24 hours in the laboratory and measured for total length was released in the experimental tank and allowed to settle. The current density was then raised from zero till the fish exhibited different reactions in successive stages. The quantity of current required for different reactions of fish along with potential difference between the electrodes were recorded. A fresh fish was used for each experiment. The conductivity of water was raised by dissolving sodium chloride in it. Continuous D. C. and impulse D. C. of different impulse and pause durations were tested for different series of experiments for fishes of different varieties. The current in μa per mm^2, was recorded as current density, δ.

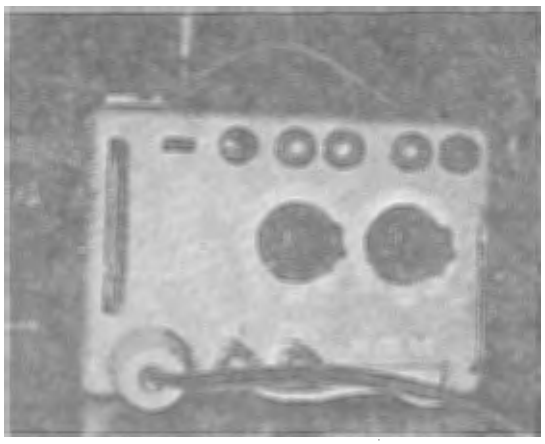

Fig 1. Showing electronic impulse transmitter

Results And Discussions

With the gradual rise of current intensity from zero, several visible reactions were noticed in fish depending on its position in the field. The fish exhibited increased gill movements, expansions of fins, tremours of body accompanied by jerks and bending of body (first reaction). A mature *S. irideus* of 186 mm started discharging milt on bending its body at a current density of 0.021 in a voltage tension of 0.502 when subjected to an impulse frequency of 82/sec at a water temperature of 12°C and conductivity of 1.6×10^{-4}/cc (table 1). In the next stage of its reaction (galvanotaxis), the fish moved violently between the electrodes for 15 to 82 seconds and ultimately stopped near either of the electrodes or in the middle at right angles to the direction of current flow. Fishes also exhibited forced involuntary movement towards the anode, near which they continued movement in a circular orbit (fig 2).

C. carpio in lower conductivity of water (2×10^{-4}/cc) moved to the cathode and stayed near it after violent movements for 14 to 108 seconds during galvanotaxis in all cases. But similar reactions to that of *S. irideus* were noticed in *C. carpio* in

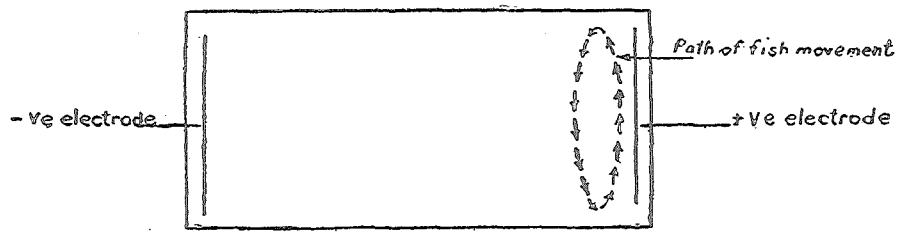

Fig 2. Movement of fish during galvanotaxis

higher water conductivity, violent movements lasting for 11 to 54 seconds. with further rise in current density beyond the threshold value for galvanotaxis, the fish sank to the bottom and lay on its side ceasing all voluntary movement (Galvanonarcosis). *S. irideus*, *C. carpio* and *I. melanotus* exhibited directional swimming towards the electrode and took either a straight or elliptical path when they lay parallel to the direction of current during galvanotaxis (Biswas, loc cit). Irregular movement between the electrodes occurred only when the fish remained in transverse position to current flow during the on set of galvanotaxis. *S. irideus* of 80 to 90 mm exhibited first reaction, galvanotaxis and galvanonarcosis in body voltages of .585 to .942, 2.34 to 2.856 and 2.825 to 5.062 respectively (Tables 1–3), which confirmed the findings of Meyer-waarden (1957). The corresponding figures for fish of the same species and length 135 to 175 mm were 1.008 to 1.957, 2.12 to 5.6 and 3.61 to 6.8 respectively. Since large fish received a greater voltage in the water than smaller ones, they could be influenced more quickly and by relatively smaller voltages (Meyer, waarden, loc cit). *S. rideus* of 156 mm showed these reactions at mean potential differences of .546, 2.139 and 5.04V respectively between their head and tail, while body voltages of .285, 1.25 and 4.56 brought about those reactions in a fish of 190 mm.

The optimum current densities for first reaction, galvanotaxis and galvanonarcosis of *S. irideus* of 166 mm average length were only .091, .163 and .642 respectively at 16°C as against .942, 1.707 and 2.615 at 3°C (table-4). However, Denzer (1956) observed low current densities at lower temperatures than those required at higher temperatures. The threshold current densities gradually decreased with increase in temperature and were minimum at 16°C. Biswas (1969) observed a decrease in threshold current densities and effective periods for narcosis with increase in temperature.

The effect of electrical influence on fish is greatly dependent on the conductivity of water mass. (Harris, 1953). *S. irideus* having a median length between 146 to 196 mm exhibited first reaction, galvanotaxis and galvanonarcosis in current densities of .042 to .144, .156 to .304 and .571 to .736 in water having conductivity of $2x10^{-4}$/cc as against .067 to .172 .271 to .519 and .642 to .894 in a higher conductivity of $10x10^{-4}$/cc in impulse D.C. of 82/sec. (Table 5).

T. tinca of 196 mm to 236 mm median length exhibited first reactions, galvanotaxis and galvanonarcosis in current densities of .204 to .682, .894 to 1.221 and 1.586 to 2.365 in water having conductivity of $2x10^{-4}$/cc in impulse D. C. of 82/ second as against .145 to .154 .35 to .438 and .682 to .792 in $10x10^{-4}$/cc water conductivity (table 6). *C. carpio* of 96 to 126mm median length showed first reaction, galvanotaxis and galvanonarcosis in current densities of .037 to .061, .313 to .46 and .948 to 1.03 in

Table 1 Threshold current density and body voltage for 1st. reaction of *S. irideus* in relation to length

Impulse frequency: 82/sec. Impulse duration: 5ms. Pause duration: 7.2 ms.

Length of fish in mm.	No. of fishes used	Temperature of water: °C	Voltage in electric field : v/cm	Conductivity of water	Mean body voltage for 1st reaction : v	Mean threshold current density in δ required for 1st reaction
80–84	11	16	.105–.120	1.5×10^{-4}/cc	.840–.984	.171–.208
85–90	12	,,	.095–.065	,,	.722–.585	.132–.063
135–140	4	,,	.145–.105	1.9×10^{-4}/cc	1.957–1.470	.284–.180
155–160	8	,,	.085–.100	,,	1.317–1.580	.103–.161
162–165	6	,,	.08–.07	,,	1.312–1.155	.115–.077
166–170	8	,,	.06–.08	,,	1.008–1.360	.057–.098
175	2	,,	.08	,,	1.4	.098
151–160	5	12	.035–.032	1.6×10^{-4}/cc	.546–.512	.027
180–186	7	,,	.027	,,	.486–.502	.021
188–190	4	,,	.022–.035	,,	.413–.546	.017–.027

Table 2 Threshold current density and body valtage for galvanotaxis of *S. irideus* in relation to length.

Impulse frequency: 82/sec. Impulse duration: 5 ms. Pause duration: 7.2 ms.

Length of fish in mm.	No. of fishes used	Temperature of water: °C	Voltage in electric field: v/cm	Conductivity of water	Mean body voltage for galvanotaxis: v	Mean threshold current density in δ required for galvanotaxis
80– 84	11	16	.30– .39	1.5×10^{-4}/cc	2.40–3.16	.70–.92
85– 90	12	,,	.32– .26	,,	2.72–2.34	.76–.60
135–140	4	,,	.25– .22	1.9×10^{-4}/cc	3.38–3.01	.57–.47
155–160	8	,,	.21– .35	,,	3.27–5.60	.47–.67
162–165	6	,,	.28– .18	,,	4.46–2.97	.37–.47
166–170	8	,,	.22–1.25	,,	2.12–4.25	.23–.57
175	2	,,	.17	,,	2.98	.35
156–160	5	12	.11– .13	1.6×10^{-4}/cc	2.14–2.00	.23
180–186	7	,,	.08– .12	,,	1.94–1.39	.09–.20
188–190	4	,,	.11– .10	,,	2.11–1.25	.18–.08

Table 3 Threshold current density and body voltage for galvanonarcosis of *S. irideus* in relation to length.

Impulse frequency: 82/sec.

Impulse duration: 5 ms.
Pause duration: 7.2 ms.

Length of fish in mm.	No. of fishes used	Temperature of water : °C	Voltage in electric field : v/cm	Conductivity of water	Mean body voltage for galvanonarcosis : v	Mean threshold current density in δ required for galvanonarcosis
80- 84	11	16	.63-.50	1.5x10-4/cc	5.1-4.1	1.1-1.3
85- 90	12	,,	.45-.53	,,	3.8-4.7	1.1-1.5
135-140	4	,,	.26-.27	1.9x10-4/cc	3.5-3.8	.6
155-160	8	,,	.38-.33	,,	5.9-5.2	.9-.8
162-165	6	,,	.33-.36	,,	5.3-5.9	.8-.9
166-170	8	,,	.24-.40	,,	4.0-6.8	.5-.9
175	2	,,	.31	,,	5.6	.7
156-160	5	12	.28	1.6x10-4/cc	5.0-4.5	.6-.7
180-186	7	,,	.26-.24	,,	4.1-4.5	.7-.5
188-190	4	,,	.27-.24	,,	5.0-4.6	.5

Table 4 Threshold current densities for different reactions of *S. irideus* in relation to different water temperatures.

Water conductivity: 1.6x10-4/cc

Impulse frequency: 82/sec.
Impulse duration: 5ms.
Pause duration: 7.2ms.

Size group in mm	No. of fishes	Mean threshold current density in δ for 1st reaction at					Mean threshold current density in δ for galvanotaxis at					Mean threshold current density in δ for galvanonarcosis at				
		3°C	6°C	11°C	15°C	16°C	3°C	6°C	11°C	15°C	16°C	3°C	6°C	11°C	15°C	16°C
131-140	18	—	—	—	.29	.22	—	—	—	.57	.53	—	—	—	.61	.77
141-150	16	—	—	—	.80	.30	—	—	—	.70	.51	—	—	—	.85	.88
151-160	17	—	—	.88	.20	.14	—	—	1.00	.43	.43	—	—	2.05	.70	.70
161-170	28	.94	.94	.70	.20	.09	1.71	1.52	0.94	.48	.16	2.62	2.05	1.91	.74	.64
171-180	28	.85	.74	.43	.14	.10	1.72	1.65	1.19	.40	.14	2.13	,,	,,	.79	.57
181-190	22	1.05	.57	.23	—	—	1.77	1.40	1.38	—	—	2.63	,,	,,	—	—
191-200	15	.57	.35	.30	—	—	1.25	1.19	0.94	—	—	2.37	1.91	1.73	—	—

Table 5 Threshold current densities for different reactions of *S. irideus* in relation to different water conductivities.

Water temperature: 16°C

Size group in mm	No. of fishes	Impulse frequency/sec	Mean threshold current density in δ for 1st reaction at		Mean threshold current density in δ for galvanotaxis at		Mean threshold current density in δ for galvanonarcosis at	
			2×10^{-4}/cc	10×10^{-4}/cc	2×10^{-4}/cc	10×10^{-4}/cc	2×10^{-4}/cc	10×10^{-4}/cc
141—150	24	82	.14	.17	.30	.52	.74	.89
161—170	,,	,,	.05	.11	.29	.37	.75	.83
171—180	,,	,,	.09	.11	.31	.36	.64	.88
181—190	,,	,,	.04	.12	.25	.39	.52	.62
191—200	,,	,,	.04	.07	.24	.27	.54	.64
141—150	25	80	.03	.13	.15	.37	.57	.76
161—170	,,	,,	.04	.11	.26	.32	.55	.57
171—180	,,	,,	.07	.12	.33	.38	.64	.68
181—190	,,	,,	.03	.11	.18	.29	.52	.60
191—200	,,	,,	.04	,,	.24	.28	.54	.76
131—140	20	78	.05	.12	.48	.31	.82	.68
141—150	,,	,,	—	,,	—	.32	—	.46
151—160	,,	,,	.03	.10	.35	.28	.69	.55
161—170	,,	,,	.04	.11	.38	.24	.79	.45
181—190	,,	,,	.06	.12	.41	,,	.68	.48
191—200	,,	,,	.40	,,	.39	.28	.69	.60

Table 6 Threshold current densities for different reactions of *T. tinca* in relation to different water conductivities

Water temperature: 16°C

Size group in mm.	No. of fishes	Impulse frequency/sec	Mean threshold current desity in δ for 1st reaction at		Mean threshold current density in δ for galvanotaxis		Mean threshold current density in δ for galvanonarcosis at	
			$2x10^{-4}$/cc	$10x10^{-4}$/cc	$2x10^{-4}$/cc	$10x10^{-4}$/cc	$2x10^{-4}$/cc	$10x10^{-4}$/cc
191—200	16	82	.68	.15	1.22	.35	2.37	.71
201—210	15	,,	.38	,,	1.20	.44	2.23	.74
211—220	20	,,	.37	—	.89	—	1.59	—
221—230	22	,,	.32	,,	.95	.42	1 81	.79
231—240	18	,,	.20	,,	1.10	,,	1.72	.68
191—200	16	78	.35	—	.90	—	1.81	—
201—210	14	,,	.30	,,	.72	.58	1.50	.65
211—220	15	,,	.35	.14	.90	.38	1.57	,,
221—230	16	,,	.31	.15	.87	.35	1.52	.59
231—240	14	,,	.39	.14	.85	.44	1.54	1.05

Table 7 Threshold current densities for different reactions of *C. carpio* in relation to different water conductivities

Water temperature: 16°C

Size group in mm	No. of fishes	Impulse frequency per sec.	Mean threshold current density in δ for 1st reaction at		Mean threshold current density in δ for galvonotaxis at		Mean threshold current density in δ for gavaronarcosis at	
			$2x10^{-4}$/cc	$10x10^{-4}$/cc	$2x10^{-4}$/cc	$10x10^{-4}$/cc	$2x10^{-4}$/cc	$10x10^{-4}$/cc
91—100	25	82	.061	.173	.313	.480	1.03	1.67
101—110	,,	,,	.052	.200	.460	.732	1.12	1.79
111—120	,,	,,	.038	.131	.369	.771	1.03	1.60
121—130	,,	,,	.037	.153	.403	.642	0.95	1.35
91—100	20	78	.113	.115	.496	.491	1.07	1.33
101—110	,,	,,	.067	.153	.484	.548	1.08	1.38
111—120	,,	,,	.042	.109	.415	.480	1.06	1.25

water having conductivity of 2x10-⁴/cc and .131 to .2, .48 to .771 and 1.35 to 1.79 respectively at 10x10-⁴/cc water conductivity in impulse D. C. of 82/second (Table 7).

The absolute threshold current densities required for galvanotaxis and galvanonarcosis of *S. fario* of 86 mm rose to .963 and 1.577 in water conductivity of 8.2x10-⁴/cc from .64 and 1.57 respectively at 2.2x10-⁴/cc when subjected to impulse D. C. of 69/second (Table 8).

Similar reactions to those of *S. irideus* were observed in the case of *G. aculeatus* when the threshold current densities for galvanotaxis and galvanonarcosis did not strictly vary inversely with rise of impulse frequency. Fishes of 46 mm median length exhibited galvanotaxis and galvanonarcosis in minimum value of current densities of .344 and 1.227 respectively in impulse frequency of 82/sec, the highest frequency tested. In lowest frequency of 65/sec, the threshold current densities for those reactions were .615 and 1.423 which were maximum for fishes of same size group (Table 9).

In lower water conductivity of 1.6x 10-⁴/cc, *S. irideus* of 166 mm median length showed first reactions, galvanotaxis and galvanonarcosis in minimum current densities of .029, 1.99 and .55 in impulse frequencies of 85/sec, 85/sec and 80/sec respectively (Table 10). Higher current densities viz; 077, .429 and .832 were required to initiate those reactions in impulse frequencies of 88/sec, 88/sec and 82/sec for fishes of similar size group.

The optimum current densities for the three reactions of *S. irideus* of median lengths 136 to 176mm were .311 to .538, .908 to 1.046 and 1.253 to 1.808 respectively in continuous D. C. which were much higher than those required in impulse D. C. of any frequency between 76 and 89/ second in water conductivity of 10x10-⁴/cc (Table 11). Though the mean threshold current densities for the reactions increased with the decrease of impulse frequencies, yet it did not follow the same rule with the gradual decrease in impulse frequency. The values of threshold current densities required for the reactions of *S. irideus* of 166mm median length were found to be minimum, viz; .086, .242 and .453 in impulse frequencies of 89/ sec, 76/ sec and 76/sec respectively in water conductivity of 10x 10-⁴/cc (Table 11), though maximum current densities, viz; .115, .365 and .784 were required to induce those reactions in impulse D. C. of 88/sec, 82/sec and 88/sec in fiishes of same size groups.

The requirement of threshold current densities for different reactions of fish varied with its position in electrical field. *S. irideus* of 80 to 90 mm required minimum current densities to show first reaction, galvanotaxis and galvanonarcosis when situated parallel to field lines. The threshold values of current densities for these reactions increased when the fish body axis was at an angle of 45° and was maximum when the fish was perpendicular to field lines (Table 12).

The requirement of optimal average current density for first reaction of *S. irideus* of 133 to 173 mm median length were minimum viz; .077 to .038 when the fish dody was parallel to field lines. The threshold value gradually increased with increase in angle between the body axis of fish and field lines and became maximum (.567 to .296) when the fish body axis was perpendicular to field lines (Table 13). Galvanotaxis set in, in current densities between .32 to .5 when fishes were parallel to electrical lines of force. But the optimum average current density showed a trend of gradual increase with increase in angle between body axis of fish and field lines and were maximum (.46 to .701) when the

Table 10 Threshold current densities for different reactions of

Water temperature: 12°C

Size group in mm.	No. of fishes	Mean threshold current density in δ for 1st reaction at					
		88/sec.	85/sec.	82/sec.	80/sec.	79/sec.	76/sec.
131–140	40	.075	—	—	—	—	.048
141–150	60	.144	—	.144	.031	—	—
151–160	80	.038	.029	—	—	.058	.033
161–170	120	.077	,,	.057	.036	.031	.036
171–180	,,	.044	,,	.092	.073	.033	.042
181–190	100	—	,,	.036	.033	.018	.057
191–200	75	—	—	.042	.036	—	.036
201–210	25	—	—	—	.031	—	—

Table 11 Threshold current densities for different reactions of

Water temperature : 12°C

Size group in mm.	No. of fishes	Mean threshold current density in δ for 1st reaction at					
		D. C.	89/sec.	88/sce.	82/sec.	80/sec.	76/sec.
131–140	75	.538	—	.096	—	—	.119
141–150	125	.411	—	.096	.173	.125	.119
151–160	100	—	.102	—	.057	.148	.104
161–170	150	.361	.086	.115	.113	.109	.109
171–180	125	.311	.117	.157	.109	.115	—
181–190	,,	—	.086	.163	.119	.109	.119
191–200	75	—	.102	—	.067	.109	—
201–210	50	—	—	.077	—	—	.119

body axis of fish was at an angle of 90° to lines of current conduction. During galvanonarcosis also, lesser current densities (.5 to .729) only were required when they stayed parallely to electrical lines of force. The requirement of threshold current density increased gradually with angle between fish body and field lines and were maximum (.85 to .942) in a position perpendicular to field lines.

In an impulse frequency of 82/ second *S. irideus* of 196mm average length showed the three reactions in .042, .242 and .538 current densities respectively in water conductivity of $2x10^{-4}$/cc as against .201, 1.221 and 2.365 respectively for *T tinca* of similar length (Table 14). In lower frequency of 78/ sec also, the requirement of optimal current densities for different reactions of the latter were more than those required by *S. irideus* of similar size. In higher conductivity of $10x10^{-4}$/ cc, *S. irideus* exhibited the reactions in current densities of .067, .211 and .642 respectively in impulse frequency of 82/ sec, as against .15, .35 and .709 respectively for *T. tinca* of same size.

Between *C. carpio* and *S. irideus* of 126 mm average length, the latter required higher current densities of .075, .433 and

S. irideus in relation to different impulse frequencies

Water conductivity: 1.6x10-⁴/cc

Mean threshold current density in δ for galvanotaxis at						Mean threshold current density in δ for galvanonarocosis at					
88/sec.	85/sec.	82/sec.	80/sec.	79/sec.	76/sec.	88/sec.	85/sec.	82/sec.	80/sec.	79/sec.	76/sec
.433	—	—	—	—	.480	1.144	—	—	—	—	.817
1.000	—	.304	.150	—	—	1.067	—	.736	.571	—	—
.365	.144	—	—	.394	.350	.761	.884	—	—	.652	.694
.429	.199	.288	.256	.223	.375	.732	.600	.832	.550	.592	.792
.320	.213	.356	.329	.250	.394	.630	.567	.638	.640	.638	.579
—	.230	.246	.179	.182	.412	—	.677	.519	.517	.565	.682
—	—	.242	.242	—	.394	—	—	.538	.540	—	.689
—	—	—	.144	—	—	—	—	—	.579	—	—

S. irideus in relation to types of current and different impulse frequencies

Water Conductivity : 10x10-⁴/cc

Mean threshold current density in δ for galvanotaxis at						Mean threshlod current density in δ for galvanonarocosis at					
D. C.	89/sec.	88/sec.	82/sec.	80/sec.	76/sec.	D. C.	89/sec.	88/sec.	82/sec.	80/sec.	76/sec
1.046	—	.315	—	—	.307	1.808	—	.961	—	—	.677
1.000	—	,,	·519	.369	.320	1.253	—	.577	.894	.761	.463
—	.309	—	.304	.309	.277	—	1.06	—	.660	.660	.548
.931	.277	.296	.365	.315	.242	1.400	.701	.784	.750	.571	.453
.908	.296	.284	.307	.304	—	,,	.750	.701	.877	.519	—
—	.277	.163	.394	.292	.238	—	.531	.307	.615	.396	.480
—	.260	—	.211	.284	—	—	.496	—	.642	.761	—
—	—	.230	—	—	.277	—	—	.753	—	—	.600

1.144 respectively for first reaction, galvanotaxis and galvanonarcosis while the former exhibited similar reactions in current densities of .037, .403 and .948 respectively in water conductivity of 2x10-⁴/cc (Table 14). But with the rise of conductivity of water to 10x10-⁴/cc, much higher current densities of . 153, .642 and 1.35 were required for the reactions of *C. carpio* as against current densities of .096, .315 and .916 for *S. irideus* of same size.

Conclusion

Reactions of fishes in successive stages occurred with the rise of current density depending on its position in electrical field. Galvanotaxis of fishes set in with unspecific violent movements for 14 to 108 seconds followed by ultimate movement to either of the electrodes or in middle in a position at right angles to the direction of current conduction. With still further rise of current density fishes exhibited galvanonarcosis ceasing all voluntary movements. The three reactions occurred on reaching the threshold potential drop between the head and tail (body voltage) besides the attainment of optimum current density. The threshold values of both current densities and body voltages were interrelated and fishes exhibited these reactions in successive stages due to the cumulative effect of density of curr-

Table 8 Threshold current densities for different reactions of *S. fario* in different water conductivities and at different impulse frequencies

Water temperature: 16°C

Size group in mm.	No. of fishes	Impluse frequency per sec.	Impluse duration in ms	Pause duration in ms	Conductivity of water:	Mean threshold current density in δ required for	
						Galvanotaxis	Galvanonarcosis
81-90	25	82	5.0	7.2	2.2×10^{-4}/cc	.527	1.203
81-90	28	78	5.7	,,	,,	.523	1.221
81-90	26	76	6.0	,,	,,	.544	1.257
81-90	22	73	7.2	6.4	,,	.640	1.157
81-90	24	69	7.2	7.2	,,	.531	1.215
81-90	18	66	8.0	,,	,,	.527	1.144
81-90	22	65	7.2	8.2	,,	.627	1.260
81-90	26	73	7.2	6.4	8.2×10^{-4}/cc	.963	1.577
81-90	22	69	7.2	7.2	,,	.800	1.530

Table 9 Threshold current densities for different reactions of *G. aculeatus* in relation to impulse current of different frequencies

Water temperature: 16°C

Water conductivity: 2.2×10^{-4}/cc

Size group in mm	No. of fishes	Impulse frequency per sec.	Impulse duration in ms	Pause duration in ms	Mean threshold current density in δ required for	
					Galvanotaxis	Galvanonarcosis
37-54	20	82	5.0	7.2	.344	1.227
37-52	24	78	5.7	,,	.571	1.365
39-52	22	76	6.0	,,	.415	1.413
40-52	22	73	7.2	6.4	.605	1.363
39-53	20	69	,,	7.2	.361	1.338
38-54	18	66	8.0	,,	.506	1.317
36-54	18	65	7.2	8.2	.615	1.423
40-54	25	61	,,	9.2	.627	1.431

Table 12 Threshold current densities for different reactions of *S. irideus* in relation to its body axis to field lines

Water temperature: 14°C
Water conductivity: 1.5x10-⁴/cc

Impulse frequency: 82/sec.
Impulse duration: 5 ms.
Pause duration: 7.2 ms.

Size of the fish in mm.	No. of fish	Mean threshold current density in δ required in relation to angle of fish body axis to field lines for 1st reaction			Galvanotaxis			Galvanonarcosis		
		I	II	III	I	II	III	I	II	III
80	30	.086	.256	.484	.484	.752	1.08	1.08	1.192	1.344
81	,,	.119	.296	.484	.484	.642	1.08	1.08	1.06	1.192
82	35	.131	.284	.484	.513	.642	.85	.827	1.08	1.192
86	25	.086	.213	.402	.484	.513	.884	.827	1.08	1.144
87	30	.057	.213	.402	.433	.513	.701	1.06	1.077	1.101
88	25	.048	.213	.433	.433	.513	.877	.827	1.06	1.077
89	30	.098	.213	.433	—	—	—	—	—	—
90	,,	.098	.213	.369	.433	.513	.701	.827	1.015	1.06

I : Parallel to lines. II : 45° angle to lines. III : Perpendicular to lines.

Table 13 Threshold current densities for different reactions of *S. irideus* in relation to angle of body axis to field lines

Water temperature : 15°C
Water conductivity: 1.9x10-⁴/cc

Impulse frequency: 82/sec.
Impulse duration: 5ms.
Pause duration: 7.2ms.

Size group in mm	No. of fishes	Mean threshold current density in δ required in relation to angle of fish body axis to field lines for First reaction						Galvanotaxis						Galvanonarocosis					
		I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI
131–135	30	—	—	—	.119	—	.460	.500	—	—	—	—	.701	.729	—	—	—	—	.850
136–140	,,	.077	—	—	—	—	.567	.433	—	—	—	—	.567	.642	—	—	.667	—	,,
151–155	,,	.038	—	—	—	—	.356	.356	—	—	—	—	.600	.642	—	—	—	—	,,
156–160	,,	.048	—	—	.132	.179	.315	—	—	—	.320	.538	,,	.642	—	—	.701	.827	,,
161–165	,,	.038	.077	—	.144	—	.356	.320	—	—	.356	.433	.567	.500	.538	.642	.667	,,	,,
166–170	,,	—	.067	—	.132	.271	.296	,,	—	—	,,	—	.565	,,	,,	,,	.701	,,	.942
171–175	,,	—		—	.098	—	—	.346	—	—	.415	—	.460	,,		—	.709	—	.827

I : Parallel. II : 10° III : 30° IV : 45° V : 80° VI : Perpendicular.

Table 14 Threshold current densities required for reactions of fishes in relation to different species.

Water temperature: 16°C

Species of fish	Average length in mm	No. of fishes used	Conductivity of water/cc	Impulse freque-ncy/sec	Mean threshold current density in δ for 1st reaction	Galvanotaxis	Galvanonarcosis
S. irideus	196	10	2x10–4	82	.042	.242	.538
–do–	,,	12	,,	78	.036	.394	.689
–do–	,,	14	10x10–4	82	.067	.211	.642
–do–	,,	8	,,	78	.119	.277	.600
T. tinca	,,	8	2x10–4	82	.204	1.221	2.365
–do–	,,	12	,,	78	.346	.904	1.811
–do–	,,	,,	10x10–4	82	.150	.350	.709
C. carpio	126	18	2x10–4	,,	.037	.403	.948
–do–	,,	16	10x10–4	,,	.153	.642	1.350
S. irideus	,,	12	2x10–4	,,	.075	.433	1.144
–do–	,,	14	10x10–4	,,	.096	.315	.961

ent in the field and difference of potential created between the head and tail of the fish which varied inversely with the length of the fish. Not only the absolute current densities between these reactions reduced with the increase in fish length, but the ratio between these reactions also decreased with the increase in fish length.

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