brief communication

Magnetic and electric characteristics of the electric fish *Gymnotus carapó*

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ABSTRACT The fresh water fish *Gymnotus carapó* produces a continuous series of weak pulsed electric fields in its surroundings and senses disturbances of this field as part of its sensory system. The electric and magnetic properties of the electric organ of this fish were studied. Magnetic fields close to the fish on the order of nT are produced by currents on the order of 10^{-4} A in the electric organ of the fish. The electromotive force, the internal resistance, the current, and the electric power of the equivalent circuit were determined noninvasively.

Biomagnetic measurements of the weak magnetic fields from the brain, heart, and other organs have opened up a new window for studying humans and other living animals noninvasively with superconducting quantum interference devices or SQUIDS (1, 2). In addition, sensitive magnetic measurements have been made on isolated axons and nerves using toroidal pick up coils that surround the axon or nerve (reference 3 and references herein). This paper describes the use of this latter technique to study the magnetic fields from the electric fish *Gymnotus carapó*, commonly known as carapó or tuvira. The "electric force" of this fresh water fish was first studied by Michael Faraday in 1838 (4). Since then much has been learned about the neurophysics of the electric organ of this fish (5). We believe this is the first report that describes the measurement of the electric and magnetic parameters of the electric organ of this fish. A preliminary publication reported the detection of the magnetic field of this fish (6).

The *carapó* produces a continuous series of low voltage pulses with a frequency of 30–70 Hz with an amplitude of 200 mV, when measured with two electrodes 1.2 cm apart in tap water. The frequency depends on the physical and chemical properties of the water. In addition, the fish can change the frequency to avoid interference from extraneous signals from nearby fish of the same species (7). This fresh water fish has poor eyesight and usually lives in turbid waters. The electric field surrounding the fish is distorted by nearby obstacles, prey, or other objects. Its electroreceptors detect these changes as part of its sensory system.

The electric organ consists of a series arrangement of electrocytes that lie in four parallel tubes on each side of the fish. The tubes are insulators, and currents produced by the electrocytes will flow longitudinally producing circularly magnetic fields as shown in Fig. 1 *b*. The tube insulation also maximizes the current flow at the extremities of the fish (8).

Fig. 1 *a* shows the experimental arrangement used for the measurements. The fish is contained in a small plastic water tank that restricts its motion. The fish's tail passes through a toroidal magnetic probe that detects the magnetic field generated by the electric organ. A pair of electrodes positioned at the extrema of the electric organ detects the electric field. The magnetic field detection is based on the time variation of the flux threaded through the toroid based on Faraday's law. The electromotive force (*emf*) produced is frequency dependent with the higher frequency components producing a stronger electromotive force. To compensate for this effect, the signal is preamplified by a low noise frequency compensated amplifier (8). The magnetic and electric signals were sent to a digital oscilloscope (Tektronix 2232) for signal storage and processing, if necessary.

The toroidal magnetic sensor was made by wrapping 200 turns of AWG 30 wire on a ferrite core with μ_r = 2,000. The ferrite toroid had an inner diameter of 9 mm, an outer diameter of 16 mm, a thickness of 5 mm, and it was encapsulated in epoxy resin to provide electric insulation. After the encapsulation the internal diameter of the probe was reduced to 6 mm. The electrical resistance was $R = 4.2\Omega$ and the inductance, $L = 31$ mH. The amplifier was a differential configuration of the TL 071 operational amplifier.

Using Ampère's law the magnetic field can be related to the electric current by the expression $\int \vec{B} \cdot d\vec{l} = \mu_0 I$. The fish tail was inserted in the probe until closely adjusted to its internal diameter to detect mainly the primary current generated by the electric organ, avoiding the detection of most of the return currents that will reduce the net primary current. The amplifier and probe were calibrated to convert the output voltage into a measure for the electric current passing through the toroidal probe.

Fig. 2 shows the electric and magnetic signals recorded without averaging when the fish was placed in tap water, with electrical conductivity σ = 4 kΩ cm. The upper trace is the current and the lower is the voltage. The signals are polyphasic and the shape of the current trace is characteristic of two current dipoles in opposite directions (i.e., quadrupole of current) travelling one after the other along the electric organ. Eight specimens having a mean length (±standard deviation) of 20 ± 2 cm and a weight of 30 ± 3 g were studied. The mean peak-to-peak

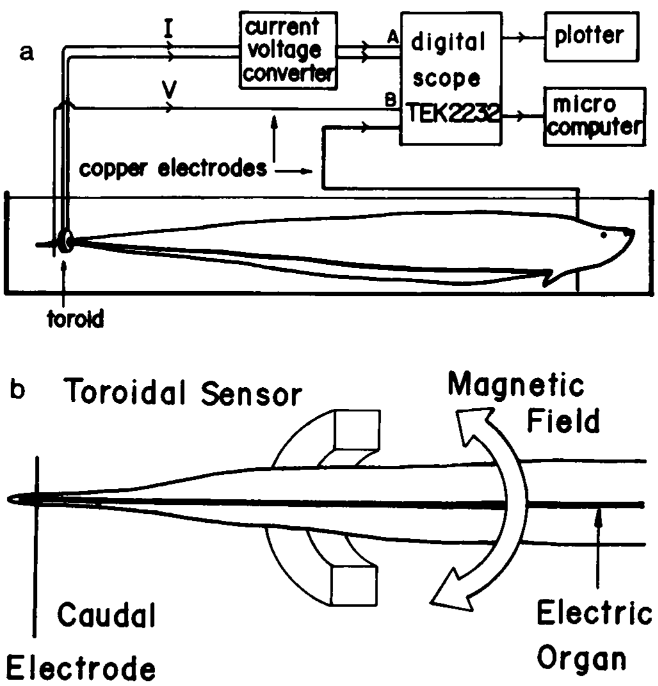

FIGURE 1 (*a*) Experimental arrangement (not to scale) employed to measure the current and voltage produced by the electric organ of the fish *Gymnotus carapó*. The current is measured by a magnetic toroidal probe and the voltage by a pair of copper electrodes. The signal picked by the magnetic sensor is preamplified by a low noise frequency compensated amplifier. A digital oscilloscope records both signals. (*b*) Details of the geometry of the electric organ relative to the toroidal sensor.

current intensity for these eight specimens was 119 ± 12 μA and the voltage, measured with electrodes placed at the extremities of the fish, was 1.2 ± 0.1 V. This last figure agrees with the one obtained when the voltage is measured with the electrodes only 1.2 cm apart because

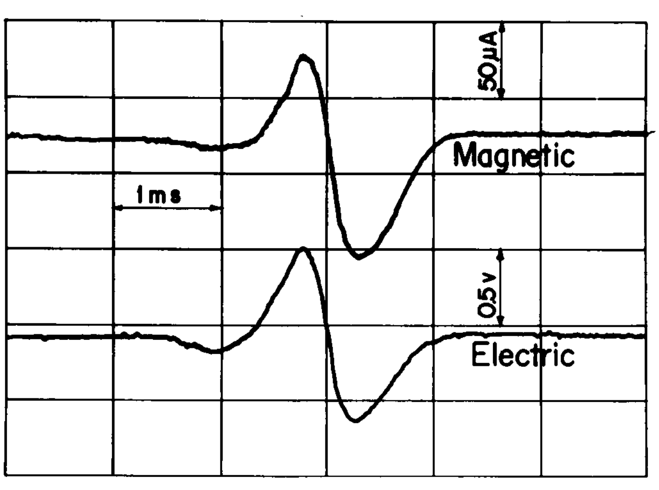

FIGURE 2 Internal current (*upper trace*) and external voltage produced by the electric organ of *Gymnotus carapó* when placed in tap water. Each horizontal division corresponds to 1 ms, vertical division is 50 μA for the current and 0.5 V for the voltage.

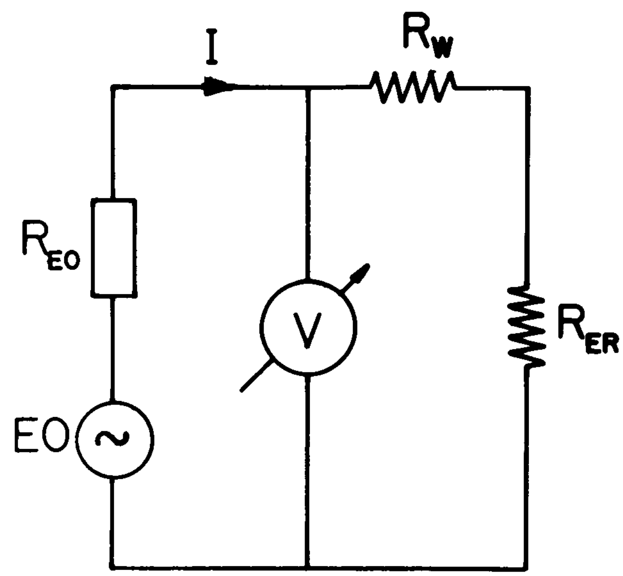

FIGURE 3 Simplified equivalent circuit of the electric organ. R_W is the equivalent water resistance connecting the signal source to the electroreceptors and R_{ER} is the equivalent resistance of the electric receptors that close the circuit. The copper electrodes detect the voltage, V, and the toroidal probe the current.

for larger distances more electrocytes contribute to the resulting voltage.

The magnetic field produced at the mean radius of the toroid by the above current is ~1.6 nT peak-to-peak.

The signal generated by the electric organ enters the surrounding water. The electric circuit is closed via electroreceptors and tissue resistance in the fish's body. The equivalent electric circuit can be modelled by a ladder of lumped electrical elements (5), as in a phone cable. This circuit can be further simplified as shown in Fig. 3. To obtain information about the electomotive force V_{EO} and the internal resistance R_{EO} the only parameter that can be externally varied is the water resistance R_W. The resistivity was adjusted by the addition of NaCl to pure deionized, bidistilled water. To avoid changes in the electrical properties of the skin and electroreceptors, the osmolarity of the water was kept equal to that of the natural habitat by the addition of appropriate amounts of Mannitol for each water resistivity.

In some experiments the open circuit voltage ($i = 0$) was measured with the fish placed out of the water with the skin dried. This imposes no harm to the fish because it also has a pulmonary respiration. The full circle in Fig. 4 shows that this point is in good agreement with the electromotive force obtained from the interception of the load line with the ordinate of this plot.

Determining the electromotive force and internal resistance of the electric organ is the same as determining them for an ordinary battery. The plot in Fig. 4 shows that the voltage varies linearly with the current (correlation coefficient, −0.98). The electromotive force can be obtained by extrapolating the current to zero. The inter-

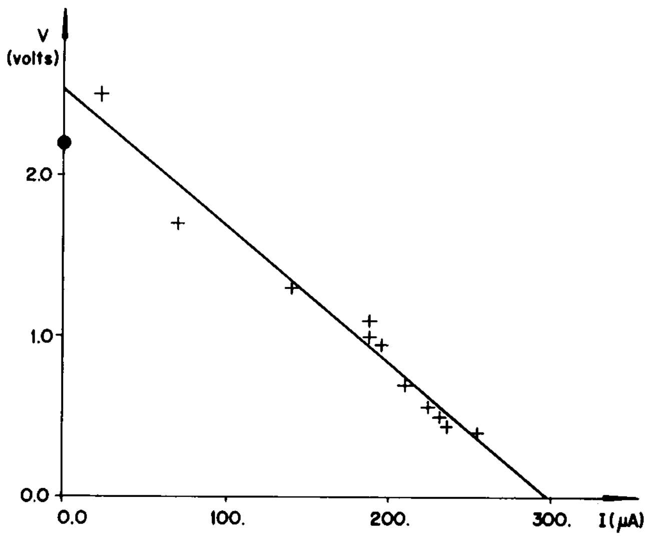

FIGURE 4 Plot of the voltage versus current generated by electric organ. The open circuit voltage give the electromotive force of $V_{EO} = 2.2$ V; the intersection of the load line with the ordinate gives an electromotive force of $V_{EO} = 2.54$ V; and the internal resistance determined from the slope is $R_{EO} = 8.7$ kΩ.

nal resistance is determined from the slope of the graph. The mean value for the electromotive force for eight specimens was (2.2 ± 0.4) V and for the internal resistance $R_{EO} = (9 \pm 2)$ kΩ. The maximum power transferred to the water will occur when the internal impedance matches the external impedance. This gave a maximum power for the peak values of voltage and current of $(1.5 \pm 0.2)\ 10^{-4}$ W. It is interesting to note that this optimum power occurred at the voltage and current determined using water with the same resistivity as in the aquarium where the fish live. One might think that the fish can extend their range of electrolocation by increasing their voltage, however, by so doing the current decreases and the smaller signal reduces the sensitivity of the electroreceptors to changes in the electric field pattern.

Our results suggest that perhaps this fish can adapt the internal resistance of its electric organ to the resistivity of the water to maximize the power transfer to the water, thus optimizing its range of electrolocation.

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