

Influence of High Steady Magnetic Fields on the Electrical Activity of the Electric Fish *Apteronotus*

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We have investigated the influence of strong dc. magnetic fields – ranging up to 10 Tesla – on the weak sinusoidal electric signals which the electro-fish *Apteronotus* is known to emit. We made the following observations:

1. The *amplitude* of the sinusoidal electric signals rises with the application of the dc. magnetic fields, increasing by about 8% in a field of 10 Tesla.

2. The *frequency* of the signals of about 570 Hz was not at all affected by the field but remained constant in fields up to 10 Tesla.

Since the electric signals of *Apteronotus* are of neural origin our experiments indicate an influence of strong dc. magnetic fields on the nervous system of this electric fish.

Various bacteria and animals are sensitive even to weak external magnetic fields of the order of the earth magnetic field ($<5 \times 10^{-5}$ T). For example, the so-called magnetotactic bacteria have been found to navigate only parallel to the geomagnetic field [1]. This surprising ability of the bacteria is made possible by a row of single domain magnetic particles of Fe_3O_4 , which were found inside the bacterial cell. There is also strong evidence that higher animals like sharks, skates, rays [2] and homing pigeons [3, 4] can detect the earth magnetic field and use it for navigational purposes. Liquid crystals, polymers and various biomolecules in solution (for example retinal rods and DNA fragments) show strong orientation in dc. magnetic fields of a few Tesla due to their diamagnetic anisotropy [5]. It has been demonstrated that magnetic fields – well below one Tesla – can strongly influence chemical reactions, as for example the processes in the photosynthetic reaction center [6]. Magnetic field-induced variations of the biological response in the retina [7], and in biological membranes [8] have been reported as well as changes of the enzymatic activities, for example, of serotonin N-acetyltransferase [9] and of thymidine kinase [10].

Recently it has been reported [11, 12] that strong dc. magnetic fields have a noticeable influence on the electrical activity of the human central nervous

system. This conclusion was drawn from the observation of magnetic field-induced changes both of the somatosensory [11] and of the auditory evoked potentials [12].

In view of the introduction of NMR tomography as a new diagnostic tool, where dc. magnetic fields up to 4 T are used, it seemed important to us to clarify the influence of strong magnetic fields on the nervous system of man by convincing experiments on simpler systems. With this motivation we have investigated the electric activity of the weakly electric fish *Apteronotus leptorhynchus* and *Apteronotus albifrons*, both living in the freshwater of Central and South America. With their neurogenic electric organs, which are located along both sides of the body from head to tail, the fish emits nearly sinusoidal electric signals. The electric organ of *Apteronotus* consists of columns of flat electric cells stacked together – electrically in series – in order to sum up the voltages of all individual electrocytes within a given column thus producing a total output voltage of nearly one volt. The frequency (500–1700 Hz) and amplitude of the electrical discharges depend for a given species mainly on the temperature and resistivity of the water respectively [13]. The waveform can also be influenced by sexual hormones [14]. But if the external conditions are not changed and the fish is at rest, both the frequency and amplitude of the electric signals are remarkably constant (within a fraction of a percent over many hours). We report here first measurements of the frequency and amplitude of the electric signals under the influence of an ex-

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ternally applied strong dc. magnetic field ranging up to 10 T.

For the experiments the fish *Apteronotus* – about 13 cm long – were placed in a plexiglas tube which in turn was located inside the axial 5 cm bore of a 10 Tesla superconducting magnet. The plexiglas tube containing the fish was continuously fed with fresh water of constant resistivity ($1.5 \text{ k}\Omega\text{cm}$) and temperature ($23 \pm 1^\circ\text{C}$). For measuring the electric signals of the fish two silver electrodes were inserted into the water: One near the head (grounded) and one near the tail, but not touching the fish. Without a magnetic field the amplitude of the sinusoidal voltage between both electrodes remained in general very constant over several hours. Altogether we performed 15 experiments with two *Apteronotus leptorhynchus* and one *Apteronotus albifrons* measuring the amplitude and frequency of their electrical signals in the presence of magnetic fields. Since the results were similar we will describe here only our observations with the fish *Apteronotus leptorhynchus*.

Fig. 1 shows a control experiment in zero magnetic field. As can be seen, the amplitude of the electric signals emitted by the fish changes by less than 1% in the course of 20 h. Typical peak-to-peak amplitudes are 0.125 volt. Also the frequency remained constant at 570 Hz. (Since the frequency is strongly temperature-dependent the water temperature has to be stabilized.)

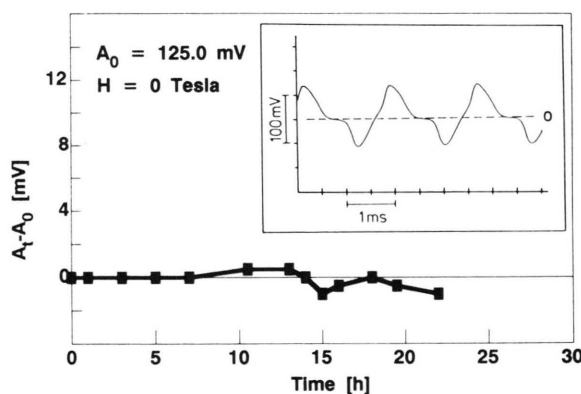


Fig. 1. The peak-to-peak amplitude A_t of the nearly sinusoidal electric signal emitted by *Apteronotus leptorhynchus* in zero magnetic field as a function of time. The initial amplitude A_0 indicated in each of the following figures is nearly the same in all experiments. The shape of the ac. electric signal is shown in the insert.

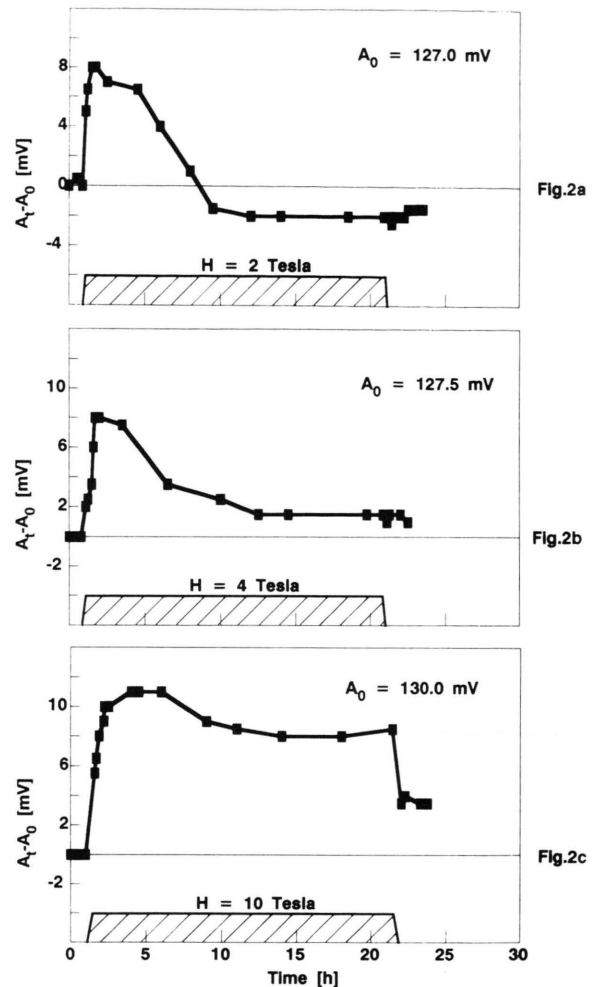


Fig. 2. The amplitude of the electric signal of *Apteronotus leptorhynchus* in steady magnetic fields of a) 2 Tesla, b) 4 Tesla and c) 10 Tesla.

Typical results for the measured voltage amplitude in high magnetic fields (of 2, 4 and 10 T) are presented in Fig. 2. For each experiment the magnetic field was slowly increased (at a rate of 0.3 T/min), then kept constant for 20 h and finally decreased slowly to zero. In all three cases we observed first a prompt increase of the amplitude by 5–8%. About 6 h later, the amplitude decreases again somewhat although the field is still applied. Only at the maximal field strength of 10 T the amplitude nearly maintains its increased value for the full 20 h of magnetic exposure.

Fig. 3 shows three consecutive experiments in fields below 2 T. They indicate that there exists a threshold of about 1 T for an influence of magnetic fields on the electric amplitude: No significant changes of the amplitude could be detected in fields below 1 T. Above 1 T, however, the amplitude steadily increased with the field strength.

In summary, our experiments show that in dc. magnetic fields above 2 Tesla and directed parallel

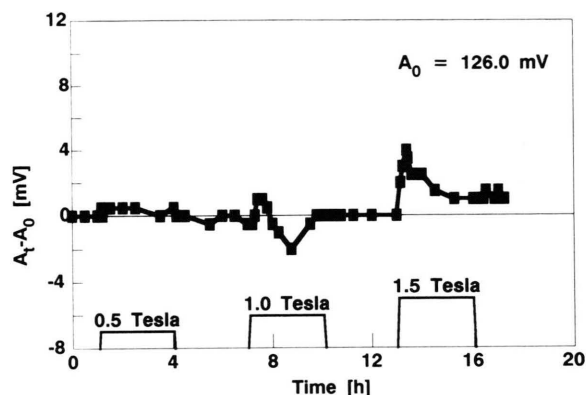


Fig. 3. The electric signal amplitude of *Apteronotus leptorhynchus* in magnetic fields of 0.5, 1.0 and 1.5 Tesla. The duration of the field exposure of 3 h was interrupted by a 3 h interval at zero field between the 3 exposures. As can be seen a clearly visible change of the amplitude occurs only in fields of 1.5 Tesla and above.

to the fish the electric signal amplitude of the weak electric fish *Apteronotus* increases by about 5–8% and that this increased amplitude is maintained for at least 5 h after switching on the field. This suggests a small but definite influence of strong magnetic fields on the nervous system of the fish.

At present, we can only speculate about the origin of this interaction of the nervous system of the fish with high magnetic fields. Perhaps the ionic conductance of the membrane or the enzymatic activity of membrane proteins depends on the magnetic field.

Finally it is also interesting to consider the time dependence of the electric amplitude after switching on the magnetic field (see Fig. 2): The instantaneous increase of the amplitude was always followed by a delayed, slower decay in the presence of the magnetic field. This seems to indicate the existence of two opposing magnetic field-dependent biochemical processes of different time constants.

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