A MINIATURIZED TELEMETRY DEVICE FOR THE TRANSMISSION OF THE ELECTRICAL ACTIVITY OF SINGLE NERVE CELLS IN THE BRAIN

James G. McElligott, John R. Zweizig and Raymond T. Kado

ABSTRACT

A telemeter is described by which the activity of individual nerve cells in the awake and unrestrained animal can be transmitted. The unit, directly incorporated into the electrode connector plug on the animal's head, possesses a high input impedance and a broad bandwidth. It is constructed inexpensively from readily available stock components and is designed to operate in the FM broadcast band.

A MINIATURIZED TELEMETRY DEVICE FOR THE TRANSMISSION OF THE ELECTRICAL ACTIVITY OF SINGLE NERVE CELLS IN THE BRAIN

James G. McElligott, John R. Zweizig and Raymond T. Kado

Introduction

During the relatively short history of telemetering biological information from humans and animals, a number of telemeters have been designed for the transmission of general, as well as specific, electrophysiological phenomena of the body. Application has been made primarily in measurements of the electromyogram (EMG), electrocardiogram (EKG), and electroencephalogram (EEG). In particular, with respect to the brain, the EEG is the bio-potential of the central nervous system that has been most often telemetered. A cursory survey of the present status of neurophysiology would indicate that this is just one of many significant electrical potentials in the brain.

Our laboratory is studying the activity of individual nerve cells or neurons as they relate to the motor activity of the cat. The neuron is the basic building block of the nervous system and imparts to the brain its unique characteristics. The electrical activity of individual nerve cells have been recorded for over 30 years but almost exclusively in anesthetized or at least in immobilized animals. Such a preparation has been necessary, for slight displacements of the electrode with respect to the cell can cause the extracellular spike potentials of the neuron to be lost. These potentials are recorded when the electrode is not more than 200 micra away from the cell. In the past few years, however, two basic approaches have been developed for recording neural spikes in the unanesthetized and freely moving animal. One is to fix the animal's head to a rigid support, thus immobilizing it but leaving the rest of the body essentially unrestrained.

The electrode, attached to the support, is lowered into the animal's head via a small microdrive (1). A second method is to implant very flexible, fine wire electrodes into the brain. Due to their extreme flexibility, they are able to maintain their relative position with respect to a particular cell in spite of slight displacements of the brain within the skull. In our laboratory, as well as in studies by others (2), the activity of a particular neuron in a freely moving animal has been recorded for days and even weeks with this technique.

Transmission and recording of the neural spike or action potential poses several unique problems and dictates the desirable characteristics of the telemetry device. Contrasted with other types of electrical activity in the brain, the neural spike possesses relatively high frequency components. A 10 kHz upper band limit is necessary in order to obtain a faithful picture of this potential. As it is sometimes necessary to record the EEG from the same electrode, a total band pass from 1 Hz to 10 kHz is desirable. Secondly, electrode impedances from 100 kΩ to several megohms demand a high input impedance. Thirdly, the size of the neural spikes that are detected by these fine wire electrodes varies from 10 to 300 μV. Inasmuch as this is superimposed on the brain's slow wave potentials (EEG) of about 200 μV the transmission of signals greater than 500 μV is necessary. Another important consideration is the signal strength of the transmitter. It should be sufficiently strong to telemeter over a distance of about 20 feet in the presence of constantly changing transmitter orientation due to the animal's movement. Finally, size and weight are important factors, for it is desirable to place the transmitter with its battery supply on the electrode connector plug that is attached to the animal's head.

The particular area of the brain under investigation in our laboratory is the cerebellum which serves as a negative feedback system in controlling such motor functions as posture, gait, balancing, and other finely graded motor activities. It is evident that the cables which usually connect the animal with the recording equipment would act as a severe hindrance in these studies. For example, if the animal is required to walk or run for a distance, an electrode cable dragging behind would considerably alter his natural gait. Telemetry is an obvious solution to this and other problems we encountered.

Circuit Design

The diagram shown in Figure 1 shows the complete telemeter circuit. Small discrete components were used as they are readily available, operate at low power levels and are of relatively low cost (cost of the circuit components was less than $30). The MMT 918 is a micro-miniature NPN silicon RF amplifier transistor and has a gain-bandwidth product of 600 MHz at 4 ma. In the design of low power transmitters, very frequently the gain-bandwidth product is given at a value of current larger than one that is compatible with reasonable battery life. Since gain-bandwidth is roughly proportional to collector current at low values of I_c, the choice of a large value allows operation at a low current and high frequency. The upper frequency limit for the circuit as shown, but with a modified tank circuit, is 170 MHz when the current level of less than 1 ma is maintained.

The input FET was chosen for its unusually low noise figure of 1.5 db at 20 Hz and 1 db at 1000 Hz. The noise figure for the MMT 918 is low enough at low frequencies to make the first stage noise figure predominate.

The voltage-variable capacitor (VVC) in the tank circuit is used to increase frequency deviation. Ultra high Q (Q's of approximately 350) varactors are available and exhibit high shift of capacitance with voltage and make ideal deviators (3). Linearity of the modulating system is of prime importance if the original signal waveform is to be preserved. The DC voltage impressed across the varactor is the magnitude of the base to collector potential and the AC component is equal to 1 plus the gain of the MMT 918 as a 0 to 15 kHz amplifier. Sampling scope traces of collector voltage show a sinusoidal carrier with an amplitude approximately 80% of supply voltage. There is no evidence of amplitude modulation even at deviations of 300 kHz.

The Micrometals powdered iron core (4) is of relatively low permeability but with a Q of 230 at 100 MHz. It provides a small and convenient form for coupling the main tank circuit to the feedback winding and the antenna lead. The high deviation sensitivity is achieved through the use of the varactor together with close coupling to the antenna, which is held at a relatively low load to reduce the "proximity effect". Other methods for the control of proximity effect include the use of a quartz crystal to prevent deviations of this type (5). The smallest commercially available quartz crystal units are housed in TO-5 transistor cases and present a size limitation for some applications.

Because of crowding in the FM broadcast band, station interference can be troublesome. Even though cores and other elements are very reproducible, it is difficult to predict transistor capacitances exactly and thus achieve an exact frequency of operation for the circuit. For this reason a trimming capacitor is added allowing minor changes to be made so that interference from strong stations can be avoided.

A number of receivers have been used successfully with the telemeter, including both modified domestic FM receivers and telemetry range receivers. To make full use of the low frequency capabilities of the unit, the discriminator output should be direct coupled to the recording device. One of the receivers used, an Astro TR-109 has a direct connection provided. Very often, however, the "video" signal is extended down to only about 5 Hz at the low frequency end, which is too high for some important components of the EEG.

Transmitter Assembly

In most brain implants on animals, the wire electrodes are soldered to a female connector plug. This, in turn, is attached to the skull by means of screws and dental cement. The transmitter module and battery supply are incorporated onto the complementary male plug (Figure 2). There are several advantages to this arrangement. First, the telemeter is external to the animal and permits easy accessibility to the batteries. In addition, with the unit attached to the connector plug, the noise level is reduced because input to the transmitter is brought as close as possible to the signal source and connecting cables to a telemetry pack are eliminated. The cat has generally from 10 to 15 flexible fine wire electrodes implanted in his brain. Since the transmitter can handle only one input at a time, a switching arrangement is necessary. This is easily accomplished on the male connector plug. A small "jumper" bar can be constructed to connect any one of the electrode pins to the input of the transmitter.

One of the prime considerations in assembling the transmitter was to make it as small and as light as possible. After potting in an epoxy resin, the transmitter is a small cylindrical module (9mm dia. x 18 mm) and weighs 2.5 g. With battery supply and male connector plug, the total weight is 20.5 g or about 0.75% of the cat's total body weight (see Table I).

At present, we are attempting to construct a multichannel telemeter using separate transmitters that operate off the same battery supply. The weight increase for each subsequent channel is only 2.5 g. Therefore, with respect to weight and size, transmission of several channels of data is feasible.

Expermiental Application

The particular transmitter described in this paper has been used in a number of behavioral situations with satisfactory results. Figure 3 is an example of individual neural spikes transmitted with negligible distortion and free from noise and artifacts. In a number of cases the data recorded by the telemeter has been of a better quality than that recorded by hard wire. With hard wire there is some cable noise that cannot be eliminated especially with these high impedance/low level signals.

Not only has telemetry proved convenient but it has proved essential in some experiments. In one situation which tests motor coordination, the cat is required to walk for ten feet on two rows of pegs that are elevated above a trough of water (Figure 4). Cats trained readily in this task since they prefer to walk on the pegs rather than in the water. Food reinforcement or general encouragement from the experimenter will induce the animal to walk back and forth. Inasmuch as a great deal of balance and fine motor coordination is required, the presence of a long cable would severely disturb his motor behavior. Other experimental procedures require handling the animal and manipulating various limbs and muscle groups. Again, for the reasons listed above, telemetry proved to be a satisfactory solution.

During many experimental sessions the only problem encountered was that of detuning when the animal scratched his head and disturbed the transmitter. The signal was lost for a short period but was recovered immediately thereafter. The proportion of time that this happens during an experiment is relatively small and does not provide any serious inconvenience. A second difficulty encountered was the loss of signal due to the directionality of the radiating element. This occurred with one of the first versions of the transmitter. The addition of a twelve inch antenna lead implanted subcutaneously along the back of the cat plus an increase in RF signal strength has eliminated this problem.

Conclusion

Thus, we have seen that with the telemeter described above, it is possible to transmit the activity of individual nerve cells in the awake and unrestrained animal. This particular telemeter is frequency modulated by a varactor which provides high deviation sensitivity. Furthermore, it possesses a high input impedance and a broad bandwidth which allows transmission of neural spikes as well as EEG. It is small and light enough to be directly attached to the electrode connector plug on the animal's head. The telemeter can be constructed inexpensively from readily available stock components and is designed to operate in the FM broadcast band. For several months, it has been used with success in several investigations involving the correlation of single cell activity in the cerebellum and finely coordinated motor behavior.

REFERENCES

1. Evarts, E. V. A technique for recording activity of subcortical neurons in moving animals. Electroenceph. Clin. Neurophysiol., 24: 83-86, 1968.

2. Olds, J. Operant conditioning of single unit responses. Proc. XXIII Int. Congr. Physiol Sci., Tokyo, 1965.

3. Norwood, M. H. and Shatz, E. Voltage variable capacitor tuning, a review. Proc IEEE, 56 788-789, 1968.

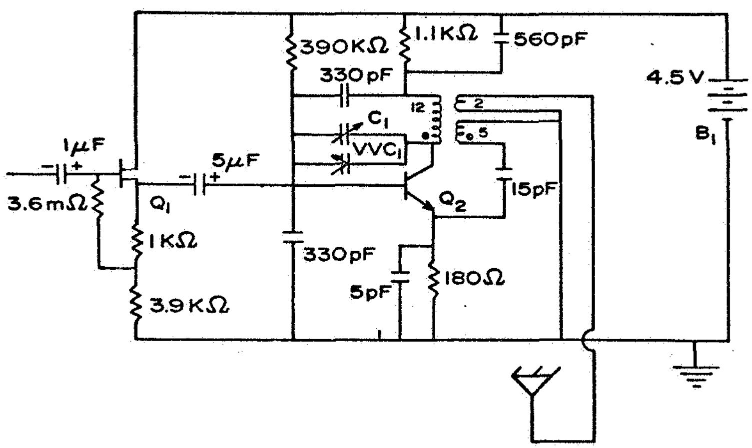
4. Micrometals, 72 East Montecito Avenue, Sierra Madre, California.

5. Kavanagh, L. A sub-miniature crystal-controlled biological transmitter. World Medical Electronics, 108-111, 1968.

TABLE I

Carrier Frequency	88 MHz (tuneable over 6 MHz)
RF Signal Strength	50 µV @ 10 ft (λ/4 antenna)
Deviation	5.0 kHz / 100 µV P.P.
DC Power Drain	1.6 mA @ 4.5 V
Battery Life	Eveready S76 E (160 mA hrs) 100 hrs @ 4.5 V
Weight	2.5 g (without battery) 20.5 g (with battery & connector plug) (0.75% of cat's weight)
Size	9 mm dia x 18 mm (without battery)
Noise	5 µV rms @ 180 kΩ 0-10 kHz 4 µV rms @ 180 kΩ 400 Hz - 10 kHz* *(bandpass used for neural spikes)
Frequency Response	2 Hz to 30 kHz (-3 db)
Maximum Signal	1.5 mV (75 kHz bandwidth)
Dynamic Range	3×10^2 (5 µV to 1500 µV)
Input Impedance	10 MΩ at 1000 Hz

MINIATURIZED TRANSMITTER FOR NEURAL SPIKES



ALL RESISTORS 1/8 WATT 5%

Q_1 2N3460 AMELCO SEMICONDUCTOR

Q_2 MMT918 MOTOROLA, INC.

VVC_1 VARICAP PG6100A (10pF) TRW SEMICONDUCTORS

C_1 OPTIONAL CAPACITOR 0.2-9pF (TO AVOID STATION INTERFERENCE) JFD MT209

T_1 PRI: 12 TURNS #30 ON T20-13 CORE
SEC: 2 TURNS #30 ON SAME CORE
SEC: 5 TURNS #30 ON SAME CORE

B_1 EVEREADY SILVER OXIDE BATTERIES # S76E

• DOT ON COIL INDICATES POSITIVE WINDING SENSE

Figure 1. Telemeter circuit

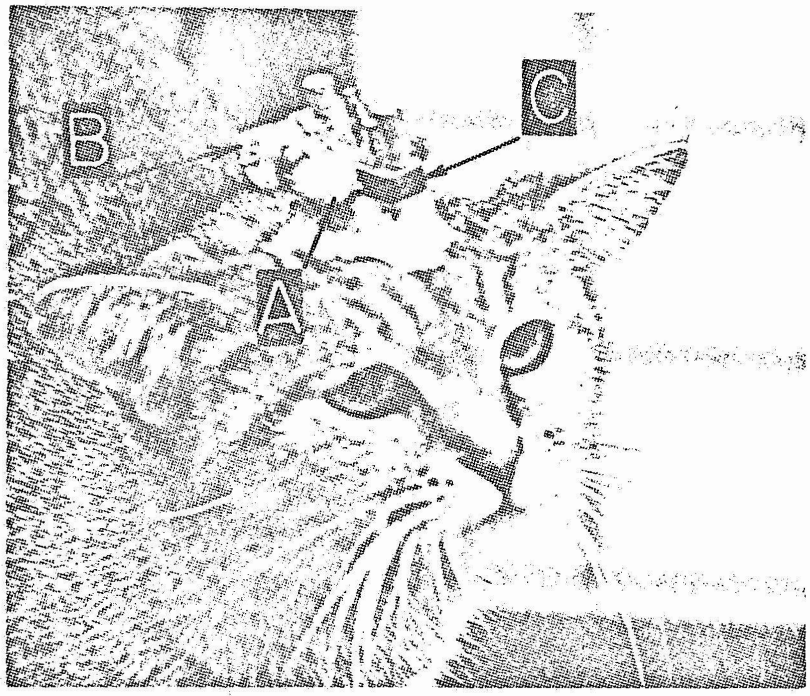
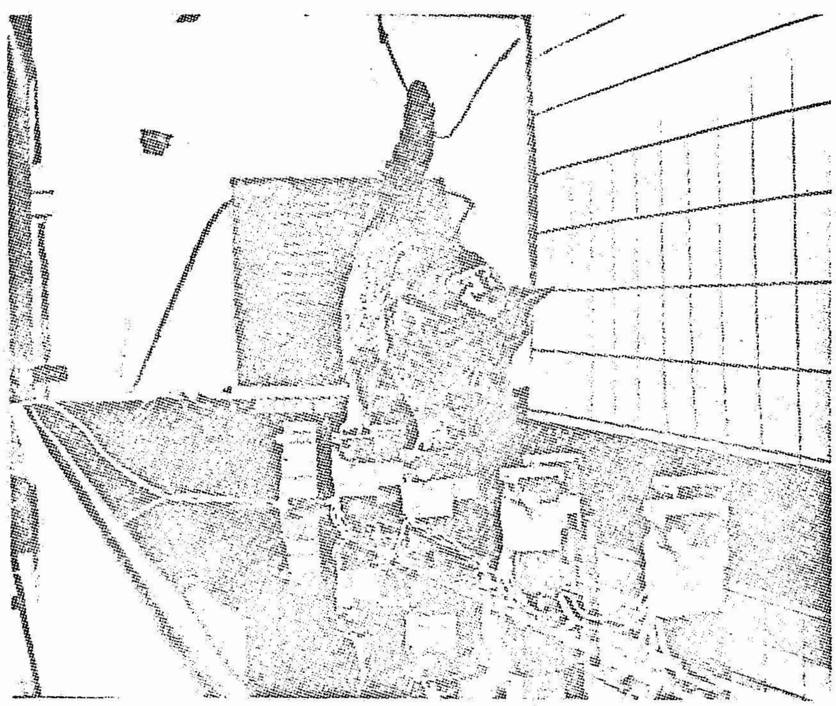


Figure 2. Transmitter module (A) and battery supply (B) incorporated on to Winchester male connector plug (C).

Figure 4. A cat performing a motor co-ordination task while the activity of single cerebella neurons are transmitted and recorded.



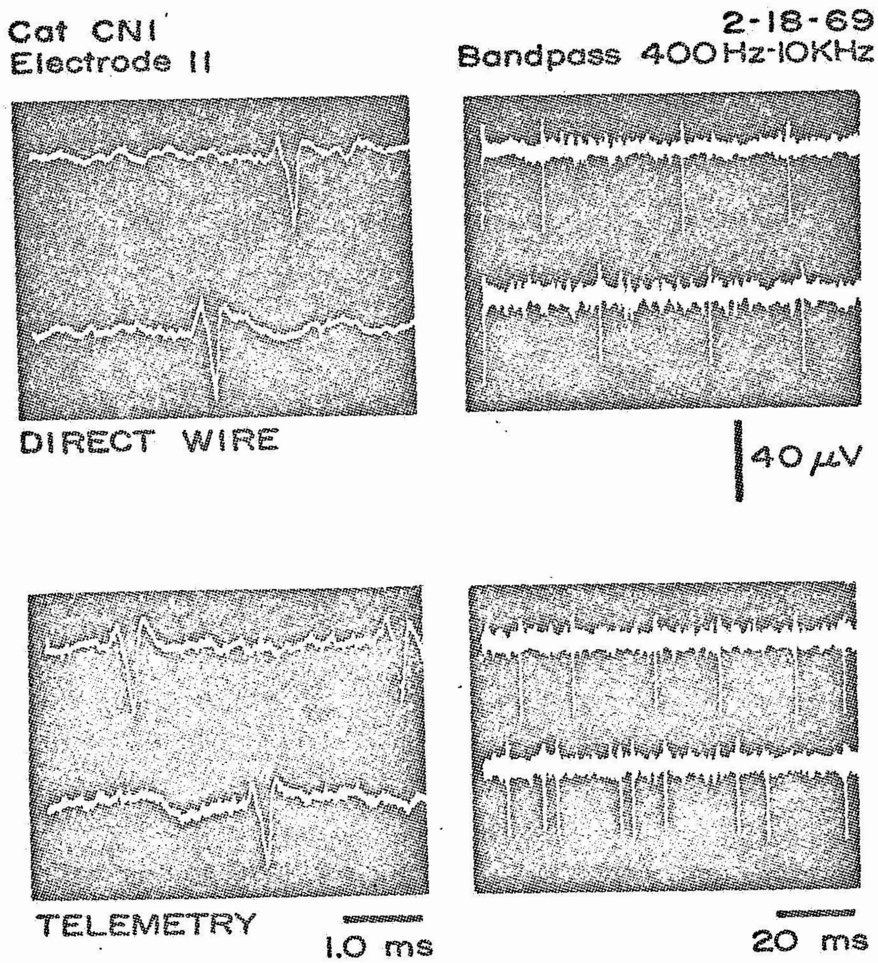


Figure 3. Examples of neural spikes recorded from a single cerebellar neuron made via direct wire and telemetry. Traces were obtained at 2 recording speeds.