# ACOUSTIC TELEMETRY FROM FISH

JOHN KANWISHER,[1] KENNETH LAWSON,[1] AND GUNNAR SUNDNES[2]

## ABSTRACT

Methods are described for monitoring physiological parameters such as temperature and electrocardiogram from free swimming fish. Information is telemetered as sound radiating from an acoustic transmitter implanted on the fish. Limitations of the technique and construction details of representative devices are covered. Uses in both behavior and physiology are considered.

Acoustic telemetry allows an investigator to study the behavior and physiology of fish under conditions which approximate their natural state. Improvements in electronic techniques permit construction of devices the size of one's little finger; these devices can transmit data such as heartbeat and temperature over ranges of several hundred meters for as long as a month. We describe here the use and constraints on sound as a means of transmitting these data. We then discuss, in detail sufficient for duplication, the construction of sample devices for transmitting, receiving, and interpreting the data. Finally, we show how these devices have been applied to specific experimental problems, and discuss the results we have obtained.

## SOUND AS A TELEMETRY MEDIUM

For ranges beyond a few meters through water, sound is the only practical form of energy for telemetry. It travels with little loss, whereas radio waves and light are rapidly absorbed. Several properties of sound in water are important. For example greater ranges are possible in fresh water than salt (one rarely has a choice in this). Low frequencies transmit further than high. For ranges up to several hundred meters, any frequency below 100 kHz is suitable. If a range of several kilometers is needed, the frequency should be less than 20 kHz. Low frequencies, however, involve longer wave lengths which implies larger transducers. In the small devices necessary for fish work these are difficult to use. Thus we most frequently employ frequencies between 40 and 80 kHz. Only in large tuna could we use a transmitter big enough to work efficiently at 20 kHz. It had an open sea range of 8 km.

The interfering background noise, which tends to obscure the signal, varies greatly at different places. In general, the shallow water tropics are noisiest. At Coconut Island in Hawaii the natural acoustic energy may be 100 times greater than that at Friday Harbor in Puget Sound. Most of the noise appears to be from bottom animals such as snapping shrimp. Man-made noise, like that from boat motors, can also be troublesome.

Relative motion between a sound source and the receiver produces a Doppler shift in the apparent frequency such that

$$\frac{\Delta f}{f} = \frac{\text{relative velocity}}{\text{velocity of sound in water}}$$

The velocity of sound in water is 1,500 m/s. A relative velocity of 1 knot shifts frequency 0.03%. This is only significant when frequency is interpreted critically, as in the depth transmitter to be described.

Additional complications arise from the interference effects due to multiple sound paths between transmitter and receiver. These are frequently troublesome in small enclosures where sound reflects from the walls. Nulls in the sound field are produced which represent momentary loss of signal. The ear has little trouble interpreting periodic signals such as electrocardiogram (EKG), but in a transcribed record these effects can be confusing (see Figure 2).

These remarks are meant to make one's ambitions more modest when considering acoustic

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[1] Woods Hole Oceanographic Institution, Woods Hole, MA 02543. Contribution No. 3277 from the Woods Hole Oceanographic Institution. This work was supported by National Science Foundation Grant GA 31987X.

[2] University of Trondheim, Trondheim, Norway.

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telemetry, particularly for work in the open sea. It is not possible to send across oceans with a miniscule device. But almost any small amount of energy will work in laboratory tanks. The low power transmitters described here are useful at distances of at least 100 m.

# CONSTRUCTION

## Heartbeat Transmitters

The cylindrical form of our devices is dictated by the transducers and batteries, both of which are round. A stainless steel tube is chosen into which the battery fits. The electronics are then packaged to this inside diameter. They are cast in epoxy resin in one end of the tube, with the heartbeat lead or thermistor coming out of the plastic. The tubular transducer is fit either inside or outside the tube, and similarly embedded in plastic to assure electrical insulation. The battery is held in place with a watertight cap on the other end. The metal case forms the indifferent reference electrode to the one placed near the heart. With the exception of the transducers (Penn Engineering & Manufacturing Co. Inc., ℅ Aquadyne, Inc., Falmouth, Mass.) parts used in these devices are routine. Parts for a heartbeat transmitter cost about $15.00.

### Large Heartbeat Transmitter

A vertebrate heart produces an electric field when it beats. A millivolt level signal from an electrode near the heart is amplified by $Q_1$ in the schematic of Figure 1. The larger voltage is used to vary the frequency of an oscillator ($Q_2$ and $Q_3$). Another amplifier ($Q_4$ to $Q_7$) after the oscillator drives a transducer at this frequency producing sound in the water. With a carrier frequency of 50 kHz the typical excursions are a few hundred hertz. Thus the EKG voltage is transformed into variations of the sound frequency. Another gain stage before the heartbeat amplifier can make the transmitter sufficiently sensitive to send signals of 100 μv or less. In this way we have been able to follow the electromyograms in the red and white muscles of fish. Figure 2 is an example of an EKG recorded from free swimming Atlantic cod, *Gadus morhua,* and Atlantic salmon, *Salmo salar*. The various sequential details of the heartbeat are clearly shown. The transmitter is 2 cm in diameter and 8 cm long.

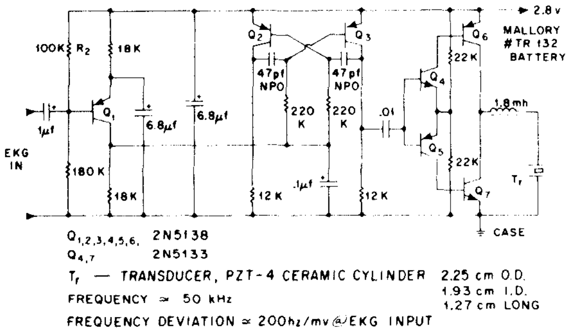


FIGURE 1.—Large heartbeat transmitter.

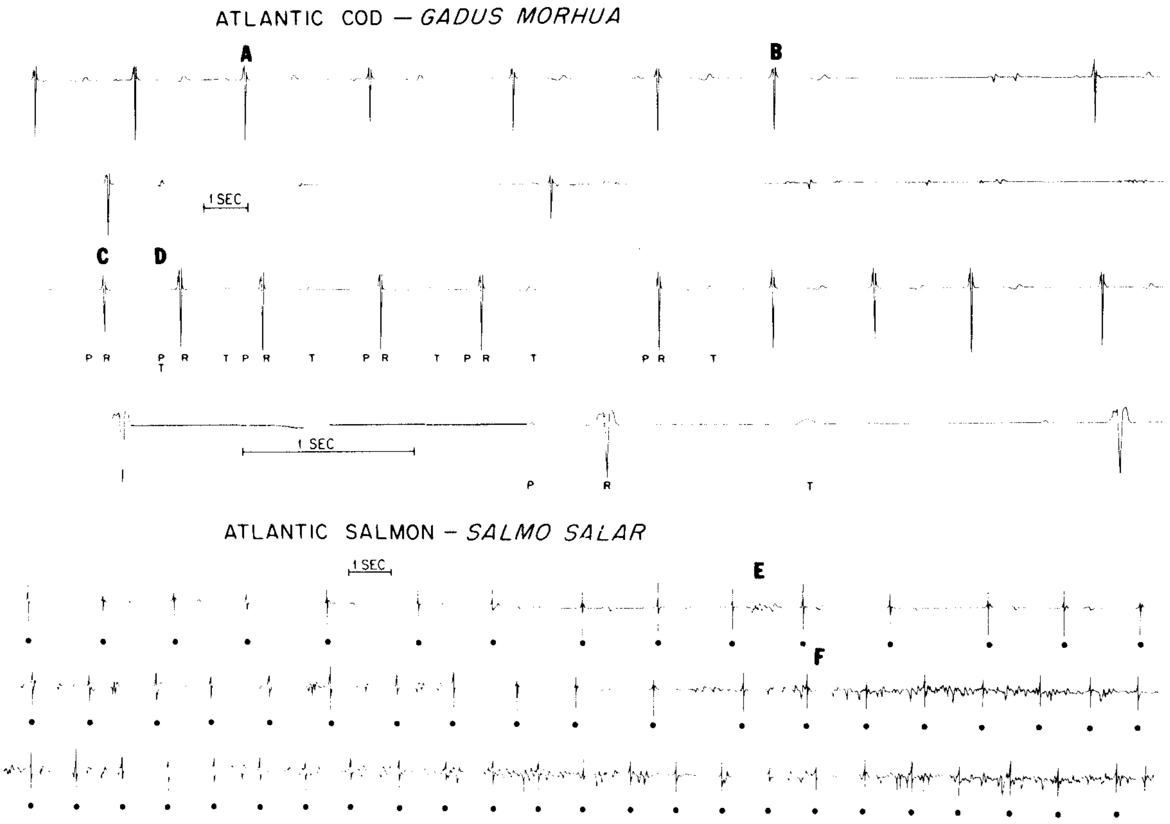
### Small Heartbeat Transmitter

Similar performance at the cost of greater effort at miniaturization can be had with the simpler and smaller transmitter shown in Figure 3, which is 1.5 cm by 7 cm. Reduced power consumption allows the same battery life (3 wk) as the larger transmitter. Be replacing $R_2$ in either transmitter with a thermistor, temperature will control the carrier frequency. The heartbeat can still be transmitted as variations around this changing frequency.

## Depth Transmitter

The depth of a fish has been a difficult variable to transmit because of the lack of practical pressure sensors. Some information about depth has been discerned from water temperature. The recent appearance of small sensitive silicon pressure sensors has made direct measurement of depth feasible. We have built a depth transmitter around such a device (Figure 4).

The DC output voltage from the pressure sensor is increased by an operational amplifer, A. These larger voltage excursions control the frequency of an oscillator in the same way as amplified heartbeat signals. The thermistor in $Q_1$ compensates the oscillator against frequency variations due to temperature. The resistor in parallel with this thermistor must be empirically chosen to optimize this compensation. This allows the received frequency to be interpreted as pressure. The frequency change is 1000 Hz/m of depth. A 20°C change in temperature causes an equivalent pressure error equal to 5 cm of water. The circuit is a voltage controlled oscillator, useful with any millivolt-level DC signals. This instru-


ATLANTIC COD — *GADUS MORHUA*

ATLANTIC SALMON - *SALMO SALAR*

FIGURE 2.—Examples of electrocardiogram from free swimming Atlantic cod and Atlantic salmon. The experimenter approached the aquarium at A and looked over at B, slowing the heart rate. When he went away the heart started at the maximum rate at C, since the T wave is piled on the next P wave at D. The Atlantic salmon also showed a slowing at E from the same source. It was chased at F, resulting in a quickly accelerating heart rate from exercise. Noise while swimming is an acoustic artifact from reflections in the tank.

ment has an operating life of 1 wk. We are using it to study gas pressure in swim bladders. With a less sensitive sensor we can determine pressures at depths equal to 1,000 m.

## Receiver

Much of our work has been done with tunable superheterodyne receivers. These employ a mechanical filter to set bandpass. Nearly equivalent results can be had from the simpler circuit of Figure 5. The hydrophone contains a frequency selective preamplifer with a voltage gain of 100. Amplification within the hydrophone is important to eliminate interference from motor ignition and radio stations. Power for this preamplifer comes down the same wire that carries signals to the receiver.

The preamplified signal is amplified another 100 times in $A_1$ (½ of a 1437 dual operational amplifier). Its output is mixed with a local oscillator in $Q_3$ to produce a signal at the audio difference frequency. This is amplified 10 times in $A_2$ and used to drive headphones. A 1-$\mu$v signal at the receiving hydrophone is clearly audible.

# RESULTS

## General

We originally developed our telemetry so it could be used with ease for human cardiac monitoring. Work with fish only required miniaturization. The usual method is to have the receiver output played through a speaker in the laboratory. This allows one to notice occasional events of interest. Such more or less casual monitoring has greatly reduced the need for observational patience. In this way we have obtained cues related to feeding and behavioral in-

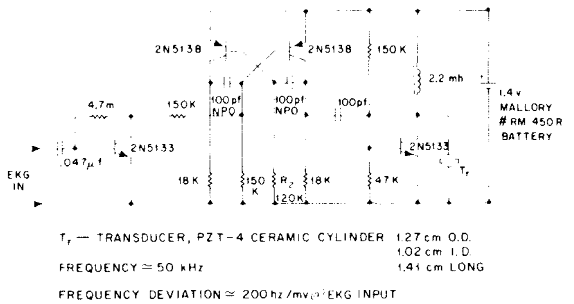


FIGURE 3.—Small heart beat transmitter.

teraction. At such times we could direct our attention more intently. Generally we have found that heart rate changes are related to specific details of a fish's physiology and also its behavior.

The transmitter can usually be carried in the stomach of the fish. It is readily inserted into an animal which has been anaesthetized with MS-222.[3] The EKG lead is brought out under the last gill arch. It is pushed under the skin immediately over the heart. The receiving hydrophone is placed against the fish so the transmitter can be monitored. There is no difficulty in interpreting when the lead placement for optimum EKG signal has been reached. The lead is then sutured in place.

The gills can now be flushed with anaesthetic-free water and the fish soon released. The entire operation takes 3 or 4 min. The fish will have been under anaerobic stress because no water has been flowing over the gills. Most specimens appear to fully recover in a few hours.

If drag is not important the transmitter can be sutured to the outside of the fish. This method has allowed us to work with plaice, *Pleuronectes platessa,* whose stomachs were too small. It was also convenient for some Atlantic cod and Atlantic salmon that repeatedly threw up a stomach tag.

## Physiological Response

When a fish is swimming we find an expected increase in heart rate, reflecting the increased oxygen transport of the cardiovascular system. In an Atlantic cod this is a measure of both the instantaneous exertion, and also of any previously incurred oxygen debt (Wardle and Kanwisher, In press). Chasing a fish to maximum fatigue can result in an increased heart rate for as long as 10 to 20 h while this debt is being repaid. Thus one gets a substantiation of the already recognized biochemical changes in muscle glycogen and lactic acid. When remote monitoring shows a rapid heart rate one cannot tell if the fish is swimming at that moment or is reflecting a previous exhaustion.

## Behavior

We were not prepared for the large component of behavioral response observed in the heart rate of all fish. Cardiac arrest is a well known response in conditioning. We found it to occur with the subtlest of cues, once the fish had recovered from initial handling. This can best be described by two anecdotes.

A plaice, which had not eaten for many months, had settled into the sand on the bottom of a 60-ft circular laboratory aquarium. It was mid-winter with low water temperatures and the fish appeared to be doing the equivalent of hibernating. In spite of this outward lethargy it responded to doors opening, relays clicking, and to any other sort of human activity in the vicinity.

It was, not unexpectedly, most sensitive to visual cues. We gradually reduced these to smaller objects moved in the visual field of the fish. The most sensitive response came early in the morning before local laboratory activity had started. At this time we could come quietly up to the tank and push a pencil a few centimeters over the edge. The plaice, 1½ m below responded by stopping its heart for 8 or 9 s.

Another incident concerned a venerable cod of more than a year in captivity. It had been re-

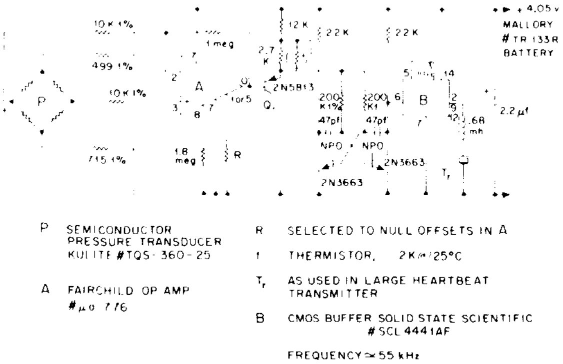


FIGURE 4.—Pressure transmitter.

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[3] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

peatedly handled for blood samples and had largely accommodated to the presence of people. Its heart slowed only when the fish was physically touched.

At one point we started toward the fish with a dip net. This was one which the fish had never seen. It stopped swimming, faced the approaching strange net, and extended its fins in what we had come to recognize as a fright response. Its heart stopped for 19 s.

We detail these because we feel that such acoustic telemetry will be a valuable adjunct to behavior and sensory studies. When we have monitored three fish simultaneously some elements of social interaction showed in their variable heart rate. In particular, competition for food was easily discerned after a few simultaneous observations of feeding and listening to the EKG. In this manner we hope to build up a behavioral repertoire which will allow us to interpret data from a fish swimming free in the ocean where it cannot be observed.

The potential effect of behavior on such physiology as oxygen consumption had been previously shown by erratic increases when a fish was confined in a respirometer (Sundnes, 1957a, b). This could be overcome by keeping cod in a laboratory aquarium for many weeks, while it became used to people and capture. Veteran fish were found to increase their $O_2$ consumption and also showed immediate color changes whenever strangers were in the laboratory. We were reluctant to accept the respiratory data until substantiated by simultaneous observations of cardiac response.

Some species are difficult to acclimate to captivity. Atlantic salmon were brought directly from a fish farm and wired for EKG transmitting. They swam for several weeks at the maximum sustainable speed until they died. From this we could only learn the maximum heart rate. A 5-kg salmon showed 60 to 62 beats/min.

Later we have had fish which were hand fed in a laboratory tank for over a year. When these fish were tagged they were immediately returned to familiar surroundings. They soon joined in feeding frenzy and showed cardiac arrest when frightened. When they were chased the heart rate quickly increased, as shown in Figure 2. Resting rates below 30 beats/min were common.

This approach was not successful with skipjack tuna, *Katsuwonus pelamis*, in Hawaii. These fast, probably warm-blooded fish were able to either get rid of our transmitter, or died in the effort. Their heart rates, however, were from 80 to 240 beats/min. This reflects their near mammallike metabolic rate. They recovered from fatigue in less than 1 h, much like man. We have used a new miniature tag (7 mm diameter × 35 mm long) successfully on mackerel, *Scomber japonicus*.

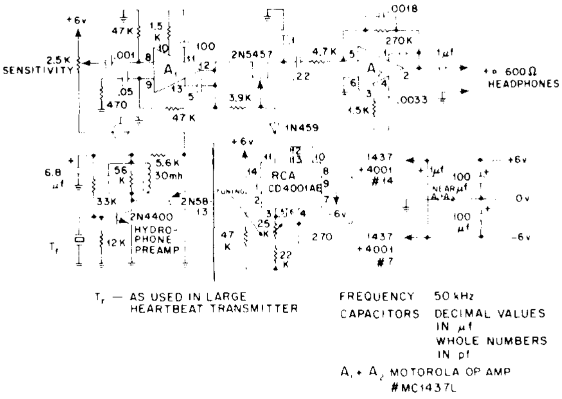

FIGURE 5.—Simple beat frequency oscillator receiver.

## CONCLUSIONS

We have tried to outline the possibilities and methods of acoustic telemetry from fish. It is a valuable adjunct in both laboratory and open water studies. In many cases, such as monitoring the body temperatures of a free-swimming tuna, it is the only way to get the desired data (Carey and Lawson, 1973). The burgeoning solid state technology promises a rapid advancement in methodology beyond the relatively simple elements we have presented here.

## LITERATURE CITED

CAREY, F. G., AND K. D. LAWSON.

1973 Temperature regulation in free-swimming bluefin tuna. Comp. Biochem. Physiol. 44A:375-392.

SUNDNES, G.

1957a. On the transport of live cod and coalfish. J. Cons. 22:191-196.

1957b. Notes on the energy metabolism of the cod (*Gadus callarias* L.) and the coalfish (*Gadus virens* L.) in relation to body size. Fiskeridir. Skr. Ser. Havunders. 11(9), 10 p.

WARDLE, C. S., AND J. W. KANWISHER.

In press. The significance of heart rate in free swimming cod. J. Mar. Physiol. Behav.