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Acoustic telemetry from human divers

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Kanwisher, J., K. Lawson, and R. Strauss. 1974. Acoustic telemetry from human divers. *Undersea Biomed. Res.* 1(1): 99-109.—Acoustic telemetry can be applied to human divers to assess the physiological stresses of diving in open water. This method provides data in real time as contrasted to recording on the diver for later playback. The report describes the use of constraints on sound as a means of transmitting ekg and respiration data; discusses the design and construction of sample devices for transmitting, receiving, and interpreting the data; and finally, shows how these devices have been applied in actual human diving research.

telemetry/acoustic
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divers

Acoustic telemetry has been used routinely for over a decade to monitor physiological parameters on free-ranging aquatic animals such as porpoises, fish, and turtles (Kanwisher and Sundnes 1967; Kanwisher and Lawson 1974). It is shown here how the method can be applied to human divers to assess physiological stresses of diving under more realistic conditions than those possible in pressure chambers.

Telemetry also provides data in real time as contrasted to recording on the diver for later playback. Monitoring by surface personnel allows the diver to be recalled to the surface

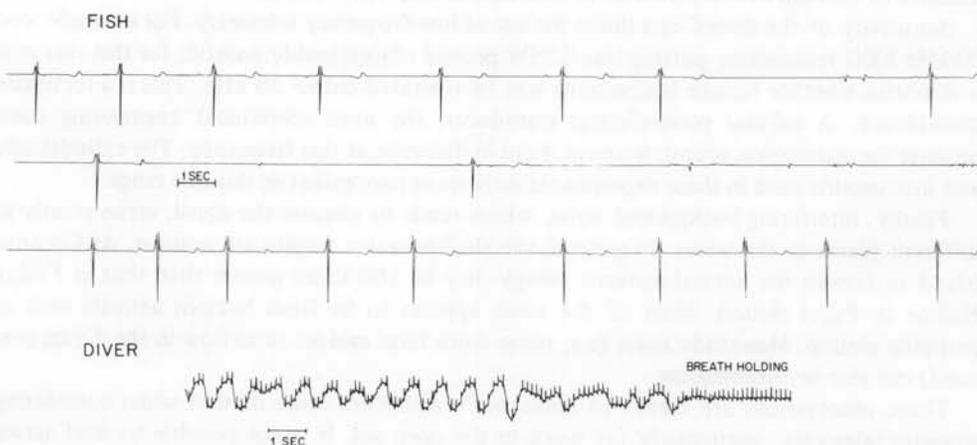


Fig. 1. EKG from free-swimming fish, and EKG plus respiration from diver. The fish shows severe tachycardia from fright.

when physiological limits are exceeded. Alternatively, the diver can be cautioned to *go slow*. This monitoring removes the need for the diver (who might be distracted by the task at hand and prideful about his professional capabilities) to take all responsibility for his own well-being. Hopefully, the method of monitoring by telemetry will add to the safety of what is, at best, a dangerous task.

Continuous improvements in electronic techniques now permit construction of acoustic transmitters the size of a little finger. These will send data such as heartbeat and temperature (from a free-swimming fish) over ranges of several hundred meters for as long as a month (Kanwisher and Lawson 1974). An example of an EKG from a codfish is shown in Fig. 1. Use of such transmitters on humans has awaited motivation, not development of the method. In the development of closed-circuit diving gear, investigators have monitored EKG and P_{O_2} extensively. This report describes the use of constraints on sound as a means of transmitting such data; discusses the design and construction of sample devices for transmitting, receiving, and interpreting the data; and, finally, shows how these devices have been applied in actual human diving research.

SOUND AS A TELEMETRY MEDIUM

Sound is the only practical form of energy for telemetry for ranges beyond a few meters through water. 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); also, low frequencies transmit farther than high frequencies. 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; however, low frequencies involve longer wavelengths, which implies larger transducers, and in small devices these are difficult to use. Thus, frequencies employed most often are between 30 and 80 kHz. To monitor large bluefin tuna, a transmitter big enough to work efficiently at 20 kHz was used; it alternately sent tissue- and water-temperature transmissions with an open-sea range of 8 km. Such a fish has been followed in the open sea for a distance of 200 km over a period of several days (Carey et al. 1971).

Sensitivity of the divers' ears limits the use of low-frequency telemetry. For example, one 20-kHz EKG transmitter putting out 0.25W proved objectionably painful; for this reason it is doubtful whether human instruments will be tolerated below 30 kHz. This is a fortunate coincidence. A tubular piezo-electric transducer, the most convenient engineering compromise for generating sound, is about 4 cm in diameter at this frequency. The cylindrically cast instruments used in these experiments were most convenient in this size range.

Finally, interfering background noise, which tends to obscure the signal, varies greatly at different places in the water. 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 (e.g. noise from boat motors or airflow in the diving gear itself) can also be troublesome.

These observations are meant to make one's ambitions more modest when considering acoustic 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 if they are acoustically quiet at the frequency used.

POWER REQUIREMENTS

An acoustic transmitter ideally sends out sound in all directions. At some remote point a receiving hydrophone intercepts the sound and feeds a converted electrical signal into a receiver. A good signal-to-noise ratio is obtained when the electrical amplitude coming from the hydrophone is $1 \mu\text{V}$ or greater. Since hydrophones used in these experiments have a typical resistance of $1,000 \Omega$, the amount of acoustic power intercepted to produce this signal is 10^{-15}W ($P = E^2/R$). This low minimum-detectable energy is the key to the successful functioning of the acoustic links. As an example, one of the smaller fish transmitters may put out $100 \mu\text{W}$ (10^{-4}W) of acoustic power. A 10%-efficient receiving hydrophone must see only 10^{-10} of this for such a transmitter to be heard, which accounts for the impressive ranges that small amounts of power allow under ideal conditions. Size, and therefore power, can be greatly increased on an instrument to be carried by a diver. One thousand times the above amount (100 mW) was minimally used in these experiments; this does not, however, lead to 1,000-fold increase in range, because of the quadratic decrease in power density with distance.

TYPES OF MODULATION

It is necessary to encode the parameter (such as EKG) to be transmitted. This is done most routinely by transforming the electrical signal into analogous frequency variations (FM). At the receiver these changes are converted back to the original electrical form and recorded on a pen writer. Such frequency modulation is fortunately the simplest to accomplish technically. It requires only sufficient frequency excursion to swamp out the small

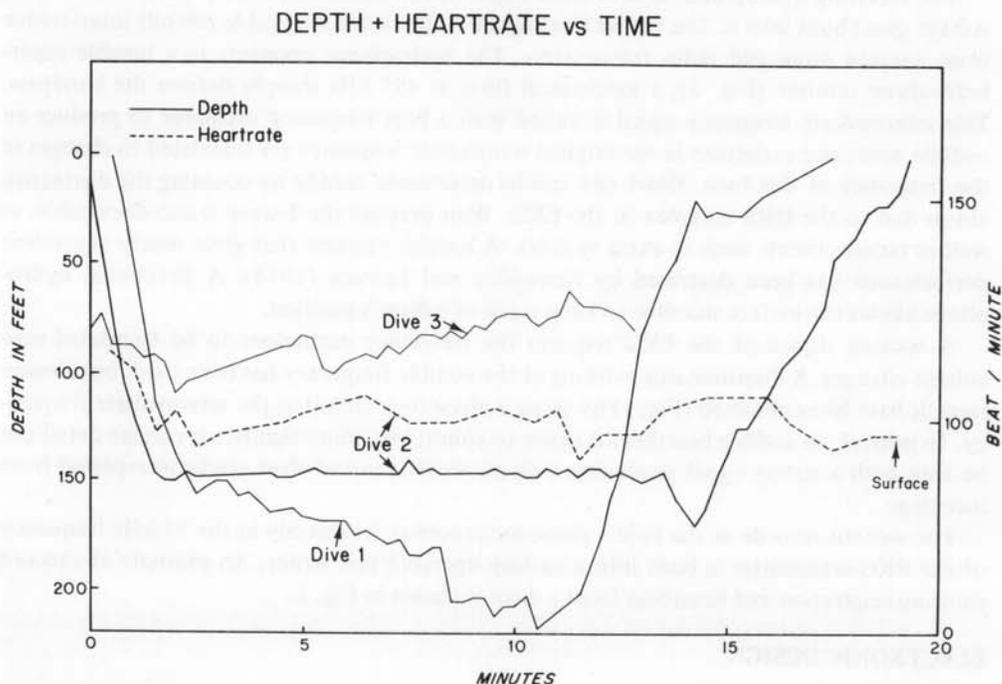


Fig. 2. Dive time versus depth and heart rate for scuba divers. Note the low heart rate during Dive 2.

amount of frequency jitter that is inherent in the multipath nature of most real acoustic situations in the water—usually below 0.1%.

Where information is needed infrequently, such as with the body temperature of a diver, the rate at which short pulses of sound are sent can be varied. The number of pulses can be counted over a period such as a minute and this number can be referred to a calibration curve to determine the temperature. Values of body temperature received once a minute provide sufficient detail to the time changes of temperature in man.

Another method of temperature encoding is to change the value of the transmitter's carrier frequency by means of a thermistor in the electronic circuit. Excursions about this slowly changing frequency can then be used to convey the EKG, in addition to temperature. At the receiver the two variables are represented by different frequency bands. Temperature is carried in the region below 0.1 Hz; the EKG is carried by modulation frequencies between 10 and 100 Hz. The two are easily separated by filtering. In this way two-channel transmission is simply accomplished.

Still another method of information encoding is to use time instead of frequency. The diving-depth transmitter sends an index pulse every 15 seconds; at a variable time after this, a second pulse is transmitted (PPM). The time is made proportional to the depth. A factor of 20 fsw in depth is used for every second of delay, and the time at the maximum calibrated depth of 200 fsw is set at 10 seconds. This still leaves a 5-second dead period before the next index pulse. If a diver goes below 200 fsw, the information pulse will be in this interval (Fig. 2).

RECEIVING

The receiving hydrophone used in these experiments has an amplifier (40 dB or 100 times voltage gain) built into it. The higher level signal in the connecting cable inhibits interference from ignition noise and radio transmitters. The hydrophone connects to a tunable super-heterodyne receiver (Fig. 3); a mechanical filter at 455 kHz sharply defines the bandpass. This intermediate frequency signal is mixed with a beat frequency oscillator to produce an audible tone, and variations in the original transmitter frequency are translated to changes in the frequency of this tone. Heart rate can be determined readily by counting the distinctive chirps due to the QRS complex in the EKG. With practice the T-wave is also discernible, as well as unique events such as extra systoles. A simpler receiver that gives nearly equivalent performance has been described by Kanwisher and Lawson (1974). A directional hydrophone allows the surface monitor to keep track of a diver's position.

A written record of the EKG requires the frequency excursions to be translated into voltage changes. A discriminator working at the audible frequency has been used, but cleaner records have been obtained (Fig. 1) by using a phase-lock circuit at the intermediate frequency. In general, an audible heartbeat is easier to count, but more significant cardiac detail can be seen with a strong signal producing a clean, written record than can be interpreted from listening.

For written records in the field a phase-lock receiver set directly at the 31-kHz frequency of the EKG transmitter is built into a battery-operated pen writer. An example of a record showing respiration and heartbeat from a diver is shown in Fig. 1.

ELECTRONIC DESIGN

Any apparatus for use on scuba divers working from a small open boat is exposed to severe physical abuse. Such operating conditions also tax the capabilities of the person at the

surface monitoring the diver. Both of these factors reward operational simplicity. The equipment presented here is that which has survived the attrition of past failures.

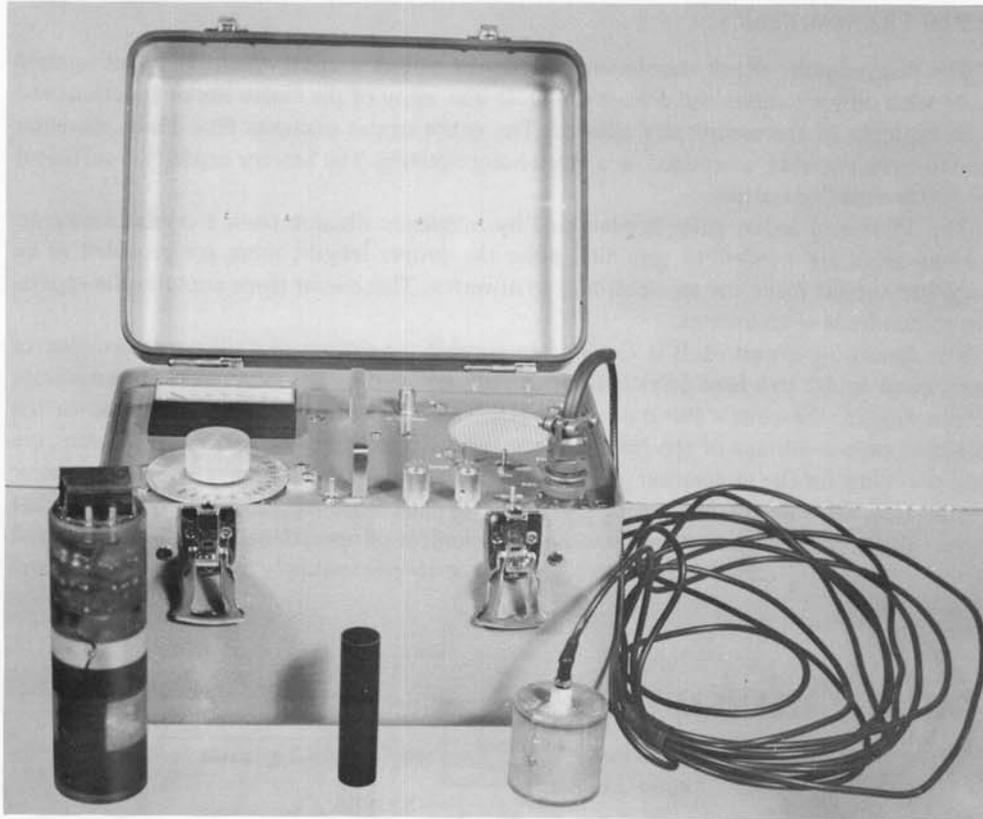


Fig. 3. Receiver plus hydrophone and also respiration and heartbeat transmitter. A fish transmitter is shown for comparison.

DESIGN PHILOSOPHY

Modern solid-state electronic components allow increasing circuit complexity with reasonable limits of size, battery drain, and cost. Proven reliability of such components gave the investigators confidence to cast finished circuits in epoxy resin instead of mounting them in a watertight case. The circuits are powered by sealed rechargeable nickel-cadmium batteries. Two metal pins, projecting from the plastic, function as the seawater switch and as charging terminals for the battery. Such instruments have functioned with good reliability to depths of over 100 msw. There is no possibility of repairing such instruments, but there has been little need to do so.

Complexity per se is rarely sufficient reason for rejecting an electronic-circuit approach to realize a certain functional end in the equipment. For versatility the investigators have used a combination of digital and analog elements. Digital is attractive because of the lower power possibilities provided by COSMOS, and analog is greatly facilitated by devices such as low-power operational amplifiers. The particular solid-state elements used undergo continuous

change as better components appear on the market. An example of a significant recent improvement would be in bilateral switching, which has been improved by COSMOS gates.

DEPTH TRANSMITTER

The delayed-pulse depth transmitter is designed to give a signal which can be interpreted easily with only a receiver and a wrist watch. It uses many of the above circuit functions and is an example of the complexity allowed. The entire circuit occupies nine 1½-in. diameter printed-circuit boards, assembled in a stack before casting. The battery capacity is sufficient for 100 hours of operation.

The 15-second index pulse is generated by frequency division from a crystal oscillator. Various gates are needed to give this pulse the proper length; these are provided in an integrated circuit made for an electronic wrist watch. This circuit alone contains the equivalent of hundreds of transistors.

The measuring circuit itself is designed to convert the output of a silicon semiconductor strain-gauge bridge to a time delay. Its operation is initiated by the index pulse. Upon receipt of this trigger, the circuit integrates a constant current until the integral is equal to the amplified output voltage of the bridge. Since this voltage is linearly related to pressure, the time necessary for the integration is also. At the completion of this integration another pulse is generated. Because the integrating current is supplied from the same supply voltage that powers the bridge, the circuit is essentially independent of operational amplifier voltage and current offsets, and offset drifts. It is also immune to power-supply changes between 8 and 15 volts.

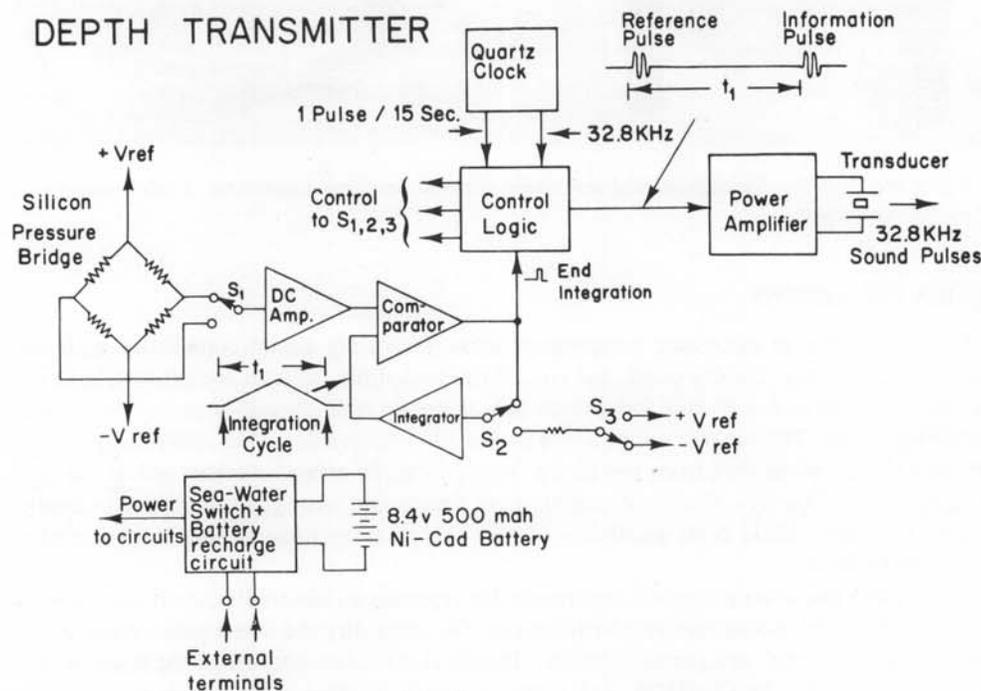


Fig. 4. Functional diagram of diver-depth transmitter circuitry.

The next index pulse, after 15 seconds, starts the integration over again whether it has been completed or not. This happens in the circuit used in these experiments if the depth is greater than 300 fsw. In such a case there will be no information pulse generated. Any malfunction in the measuring circuit still allows these index pulses to be generated.

The index and information pulses, which last 30 and 100 milliseconds (msec) respectively, are used to turn on the depth transmitter. The output of the timing oscillator (32.768 kHz) is gated to a power amplifier by these pulses. The power is 2 watts (W). A block diagram and some of the waveforms are shown in Fig. 4.

The 15-second interval between the index pulses is determined with crystal precision (.001% over a range of 10°-25° C). As the diver moves farther from the boat the pulse will arrive later because of the added time of sound traveling from the diver to the boat; at 1 mile the pulse will be approximately 1 second late. Even though this time delay is affected by both water temperature and salinity, it can still be used to determine the diver's distance from the boat. Accumulated time-error over 1 hour for a reasonable oscillator is less than 36 msec, which represents a distance error of 180 ft. To make use of the potential accuracy in this technique it is necessary to use an electronic method of time determination. As the diver leaves the boat the oscillator located in the boat is synchronized with the one worn by the diver. Its pulse is then used to start counting pulses from the oscillator worn by the diver. The received index pulse stops the count and the number of cycles tells the distance to the diver. Depth is judged most accurately by the time between the two pulses from the diver's transmitter, since the information pulse is delayed in the same way that the index pulse is delayed.

EKG AND RESPIRATION TRANSMITTER

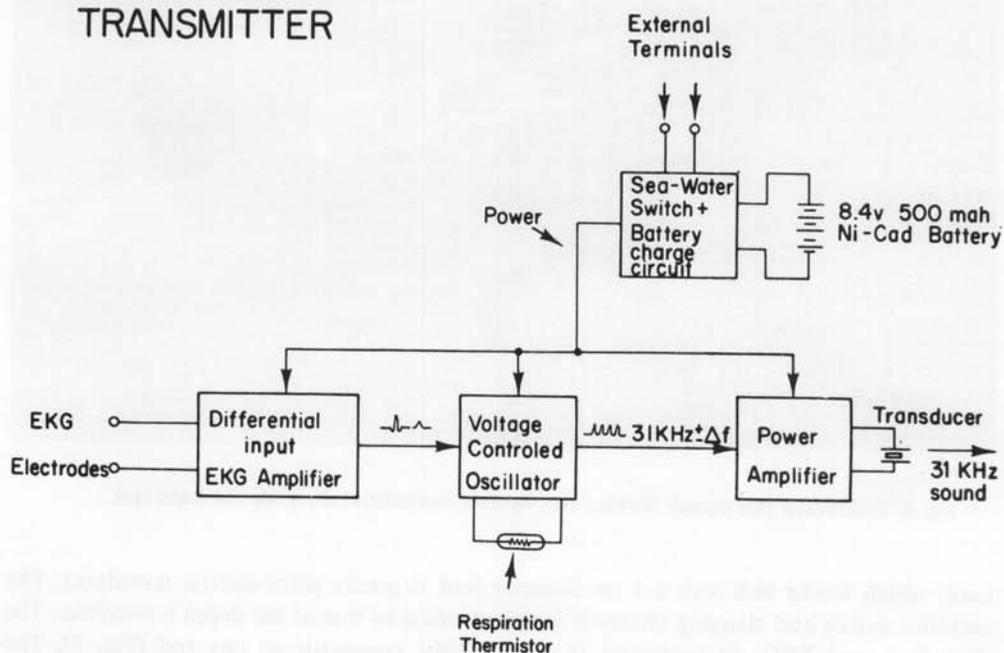


Fig. 5. Functional diagram of diver EKG and respiration transmitter.

EKG AND RESPIRATION TRANSMITTER

It has been mentioned how frequency modulation is the simplest method of transmitting low-frequency information. For heartbeat and respiration a composite modulating waveform is generated. The human EKG is generally 1 to 2 mV in amplitude, and is amplified 100 times in a circuit that strongly rejects components in phase at the two electrodes. Such common-mode rejection helps eliminate unwanted muscle potentials due to exercise.

Respiration is sensed with a thermistor in the scuba mouth-piece; the thermistor senses air-temperature fluctuation from inhalation and exhalation. Amplitude of this respiration signal is kept below that of the EKG; the ear can readily count the breathing and the heartbeats separately.

The oscillator modulated by this composite waveform is an astable multivibrator controlled at the common-base return; its stability is not critical. It can directly drive a power amplifier connected to a transducer. As in the depth transmitter, a frequency near 30 kHz is



Fig. 6. Underwater photograph showing two separate transmitters alongside the scuba tank.

used, which works well with a 4 cm-diameter lead zirconate piezo-electric transducer. The seawater switch and charging electrode is also identical to that of the depth transmitter. The thermistor and EKG electrodes go to a watertight connector on one end (Fig. 3). The received composite signal from a diver is shown in Fig. 1 and the circuit in Fig. 5.

METHODS AND RESULTS

SCUBA DIVING

Equipment described here was used to study a group of Hawaiian fishermen, who used scuba gear for spear fishing and trapsetting at depths of 200 fsw or greater. The fishermen were experienced divers, yet they apparently did not follow recommended decompression procedures and they seldom were able to give precise information on the depth history of a dive. In this study depth and heartbeat were telemetered with the acoustic transmitters shown in Fig. 6. A diver proceeded with his diving in a normal fashion after the EKG electrodes had been applied.

To enable investigators to listen from the boat, the receiving hydrophone was dangled a few meters beneath the surface, which reduced boat and motor noises to a tolerable level. It is possible to hear and count heartbeats in the presence of considerable interference since the EKG produces a distinctive signature. Most prominent is the excursion due to the QRS complex, which can readily be counted. A feeling of rhythm makes it easy to sense the large changes that undue strain produces. The heart rate can be accurately counted later, on shore, by tape-recording the receiver acoustic output. The tone from the beat-frequency oscillator receiver is left on continuously when a diver is down; large changes in pitch reflect the

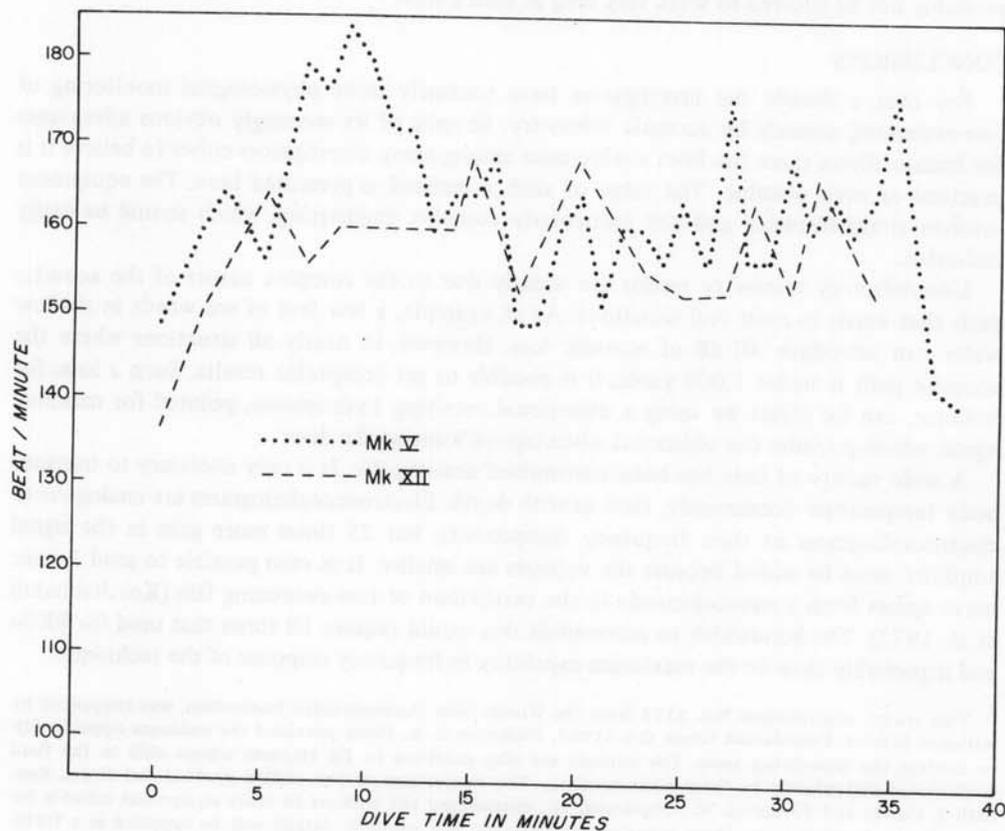


Fig. 7. Dive time versus heart rate with Navy standard (Mark V) and prototype (Mark XII) hardhat diving rigs. Note the 184 beats/min after 10 minutes with the Mark V. (From Armstrong et al. 1974.)

waveform of the diver's EKG.

The depth and heart rate curves in Fig. 2 illustrate the type of data collected using this method. Dive 2 in particular shows the rapid rate of ascent that these fishermen sometimes use. During this dive the fishermen's heart rate stayed in the neighborhood of 100 beats/min. Such a diver is clearly at ease in the water. The low rate implies a low cardiac output. This may contribute to a smaller amount of gas in the tissues, which, in turn, allows a more rapid decompression.

HARDHAT DIVING

In some recent hardhat diving tests (Armstrong et al. 1974) the decision was made to use telemetry rather than a handwire connection. Past experience had shown that it was awkward to maintain the integrity of an electrical umbilical cord. In the tests a diver was required to perform standard work tasks while his physiological stress was monitored. The sound transmitter was put in a pocket on the diving suit and the EKG leads were run through the cuff and up the sleeve.

Data in Fig. 7 indicate that a diver in an improved diving rig can perform standard work with less strain. The maximum heart rate of 184 beats/min must be close to maximum for the diver, which demonstrates the value of having real-time data during a dive. A diver would probably not be allowed to work very long at such a rate.

CONCLUSIONS

For over a decade the investigators have routinely done physiological monitoring of free-swimming animals by acoustic telemetry. In spite of its seemingly obvious advantages for human divers there has been a reluctance among many investigators either to believe it is practical or even possible. The value of such a method is presented here. The equipment involves straightforward and not particularly complex engineering, which should be easily realizable.

Unsatisfactory telemetry results are usually due to the complex nature of the acoustic path that exists in most real situations. As an example, a few feet of sea weeds in shallow water can introduce 40 dB of acoustic loss. However, in nearly all situations where the acoustic path is under 1,000 yards, it is possible to get acceptable results. Such a loss, for instance, can be offset by using a directional receiving hydrophone, pointed for maximal signal, which provides the additional advantage of locating the diver.

A wide variety of data has been transmitted acoustically. It is only necessary to transmit body temperature occasionally, such as with depth. Electroencephalograms are analogous to electrocardiograms in their frequency components, but 25 times more gain in the signal amplifier must be added because the voltages are smaller. It is even possible to send 1-msec nerve spikes from a microelectrode in the cerebellum of free-swimming fish (Kotchabhakdi et al. 1973). The bandwidth to accomplish this would require 10 times that used for EKGs and is probably close to the maximum capability in frequency response of the technique.

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