# BIOMEDICAL TELEMETRY

# BIOTELEMETRY

# TELEMETRY IN MEDICINE

# MEDICAL TELEMETRY

The word *biotelemetry* is actually an abbreviation of biomedical telemetry, which means that the measurement of different electrical and nonelectrical values measured on human or animal subjects are transmitted contactless to a stationary place. When we refer to measurements on human subjects, we are generally talking about patients in hospitals or as follow-up in the rehabilitation process, where freedom of movement is required. Biotelemetry also can be applied to athletes. The most measured physiological variables are heart and brain potentials known as electrocardiogram (*ECG*) and electroencephalogram (*EEG*) and, for athletes, muscle potentials [i.e., electromyography (*EMG*) and accelerations or forces]. In hospitals, in intensive care units or in wards where patient monitoring is performed, the radio frequency (*RF*) telemetry often is applied between the free-moving patient and the bedside monitor or central unit. The RF telemetry allows the patient more freedom and eliminates the need for nurses to be present when the patient needs to leave the bed. The nonelectrical values that are most often measured are ECG blood pressure, temperature, oxygen saturation, myocardial ischemia (by ST-level), and respiration. Biologists and human ecologists have great interest in measuring similar values for animals. Biotelemetry allows us to receive quantitative data from freely moving animals in their normal unconfined environment without disturbing the transmitter, which must be small and lightweight in relation to the animal's size and should not exceed 1% of the body weight. For the ecologists and biologists, the study of homing and migration of birds and terrestrial and aquatic animals is of great interest.

Besides telemetry over great distances, biotelemetry over very short distances is also realized when a transmitter is implanted under the skin or swallowed by the patient or animal. In the latter case, a receiver loop antenna is located over the patient close to the place where the transmitter is implanted. The different processes in the patient's intestines such as pressure, temperature, or pH-value can be investigated and measured. Swallowed transmitters are usually called endoradiosondes. This sonde passes through the stomach and all the intestines transmitting data until it reaches the exit.

## BIOTELEMETRY SYSTEMS

A biotelemetry system consists of a transmitter and a receiver with a transmission link between, as shown in Fig. 1. Transmitted information can be a biopotential or a nonelectric value like arterial pressure, respiration, or body temperature and pH value. The transducers convert nonelectrical values into electrical signals. However, for biopotential measurements, adequate electrodes must be used. The voltage at the output of the transducer or on the electrodes is very low (in the range of a few microvolts to about 10 mV), which must be amplified by an amplifier. This measured signal must change the amplitude or frequency of the "carrier" [i.e., high-frequency (*HF*) signal that carries information and enables transmission]. This process is called modulation. The modulated HF signal on the receiver side usually is low, depending on the distance between the transmitter and the receiver and is influenced by outside noise. The receiver must first amplify this low signal directly or by the heterodyne principle and then demodulate it by a demodulator to obtain the same signal waveshape as on the transmitter input. The same process occurs between a radio station and a radio receiver, except that the microphone is replaced by a transducer and the loudspeaker is replaced by a penrecorder or some other display. For HF transmission, two antennas are required on the transmission and receiving side, which must be in resonance with the carrier frequency. The length of the antenna is usually one-quarter wave length $\lambda/4$ for a whip antenna and $\lambda/2$ for a dipole antenna. In biotelemetry, loop antennas or coils for implants are also in use. This is the wireless transmission realized by RF electromagnetic waves.

Wireless transmission can also be accomplished by using infrared radiation or ultrasound. Biotelemetry over wires is used less frequently because the patient cannot move about freely, being limited to short distances. However, if the patient is stationary, telephone lines can be used for long distances. Telephone lines are used also in telemedicine where pictures can also be transmitted over the Internet. The wire and wireless systems can be combined in monitoring a patient at home, with the short-range wireless system connected to the telephone system. However, telemetry over wires, while trivial, will not be considered here.

## MODULATION MODES

Between amplitude modulation (*AM*) and frequency modulation (*FM*), FM has the explicit advantage. AM is sensitive to the patient's movement, which changes the signal amplitude as well as the reflections from the walls inside the room. AM is also very sensitive to noise. FM, in contrast, does not have these drawbacks because the information is included in the frequency changes of the carrier frequency $f_0$, and the amplitude changes of the signal do not influence the transmitter information. The deviation of the frequency $\Delta f$ from the carrier frequency $f_0$ is proportional to the signal voltage. In addition, FM electronic circuits can be very simple if only short distances are to be spanned (Fig. 2).

For greater energy saving pulse modulation (*PM*) is more appropriate because of low duty cycle. In this case the consuming up power is much lower and is reduced mostly between 0.05 to 0.005 times in comparison to continuous power supply. This means that the pulse current can be 20 to 200 times stronger than average current con-
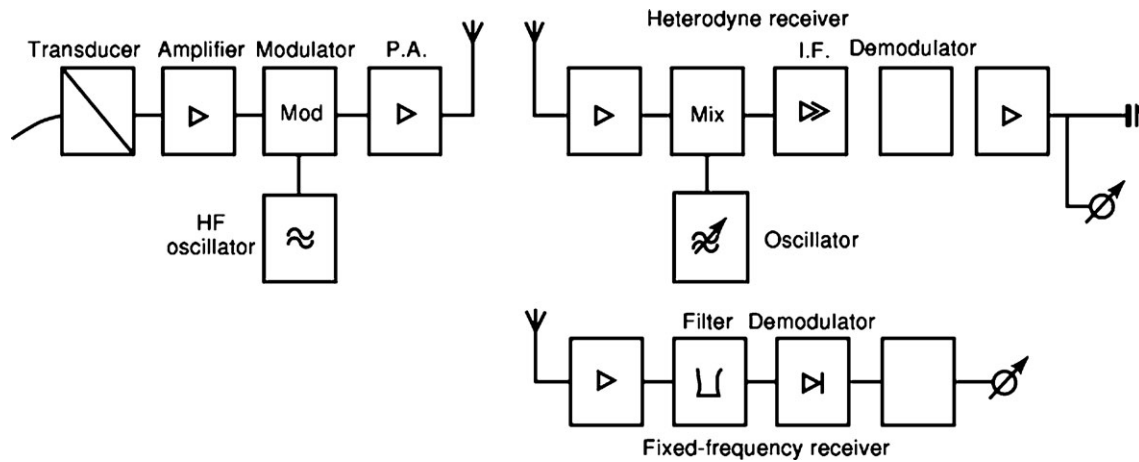
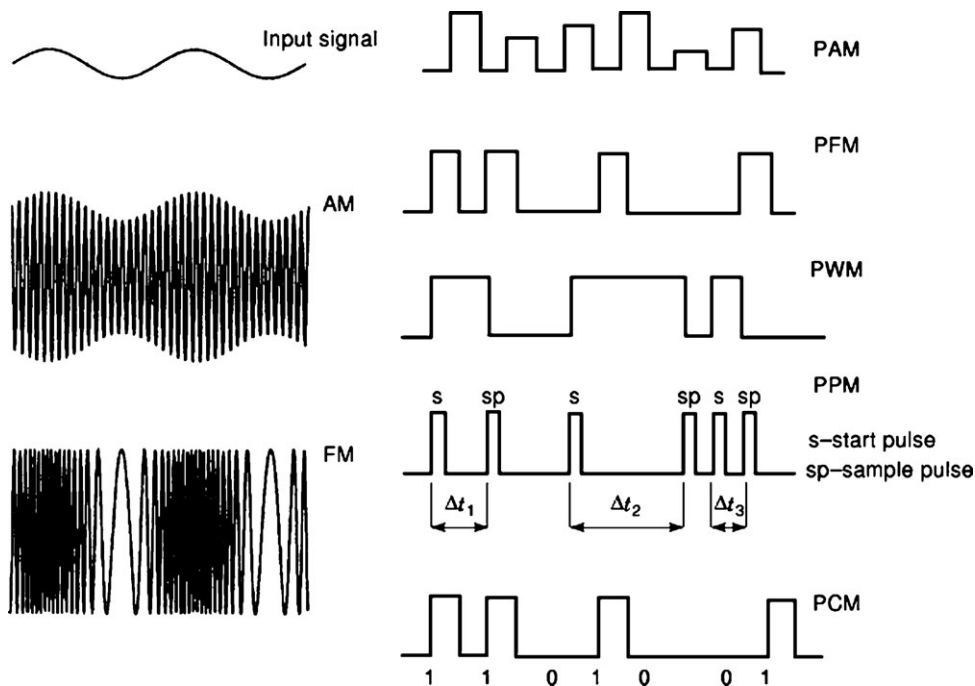**Figure 1.** Biotelemetry system: transmitter and receiver (heterodyne and fixed-frequency).



**Figure 2.** Amplitude, frequency, and pulse modulation.

sumption. The information or measured value can change the pulse amplitude, which is called pulse-amplitude modulation (*PAM*), or the pulse frequency, which is called pulse frequency modulation (*PFM*). When the pulse width changes but the frequency and interval between pulses do not change, this modulation is called pulse width modulation (*PWM*). However, when the time interval $\Delta t$ between pulses changes and the pulse width does not change, this is called pulse position modulation (*PPM*). The third possibility is pulse code modulation (*PCM*), wherein one amplitude (8 or 12 pulses) is used, depending on the resolution required. The $n$-bit resolution has $2^n$ quantum levels. The pulse width is equal in this case to the interval between pulses. PPM is the most energy efficient because short pulses with the lowest duty-cycle can be created, and only two pulses are required for each sample of the signal. Those types of modulation are shown in Fig. 2.

It is quite evident from the previous discussion that the transmitter is a crucial part of biotelemetry systems, because it is carried by the patient or the animal and, consequently, should be small and lightweight. The transmitter should not get in the animal's way, especially for an animal, which is not aware of carrying such an object. It is obvious that the transmitter can be much bigger when carried by an elephant, bear, or horse than by a small bird or insect like a grasshopper or honey bee, which may weigh only 2 g. Moreover, Winter (1) reports that an ECG transmitter made in surface-mount SMD technology, which weighs 0.45 g, consumes 15 $\mu$A and has a range of 2 m to 5 m. On the other hand, the receiver has no size or weight restrictions because it is, in most cases, stationary. The reverse situation occurs during biostimulation when the receiver is implanted inside the body and must be as small as possible, whereas the transmitter has no size or weight restrictions.
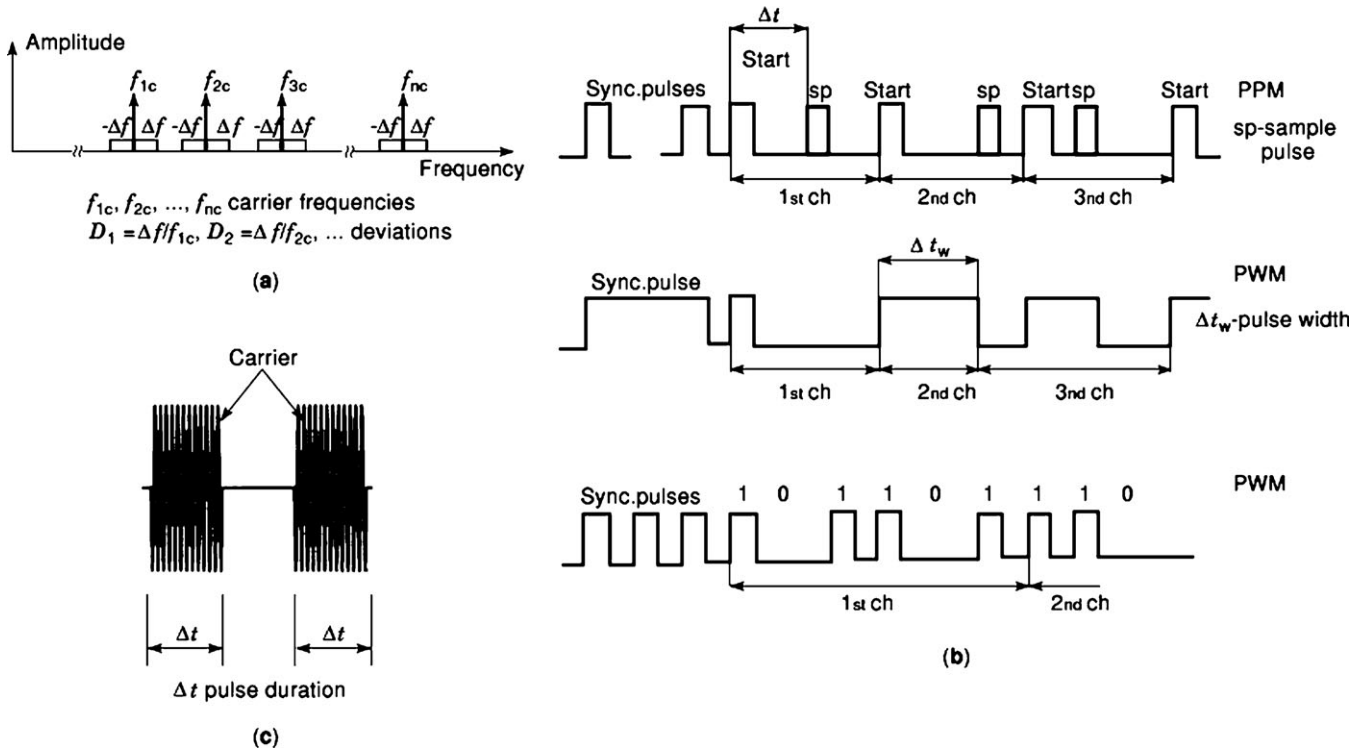
**Figure 3.** (a) Frequency, (b) time division modulation, and (c) amplitude shift keying.

If the signal must be transmitted from a small animal or if a transmitter has to be implanted, in which case small size is required, only one signal or channel is often measured and transmitted. However, in a clinical application, often more variables must be measured, and a multichannel system is required (1). When more measured data need to be transmitted over only one link or medium, each separately measured type of information is called a channel. To transmit more data simultaneously, each channel can have its own carrier frequency, which is called frequency division multiplexing. However, frequencies from one channel should not enter into the frequency domain of another channel [Fig. 3(a)]. The channels can be transmitted in time sequences which is called time division multiplexing and are represented in Fig. 3(b). To know when to start a series of channels, at least one synchronization pulse is required. In biotelemetry, time multiplexing is mostly used.

When an RF electromagnetic wave is transmitted, each pulse must modulate an RF frequency oscillator in on-off key mode. The same is true for ultrasonic waves (2, 3). In each case, a pulse of duration $t_p$ must span a few periods $n$ of the transmitted signal [i.e., the $f_{osc} \geq n/t_p$ as shown in Fig. 3(c)]. In infrared telemetry, such an oscillator is not required, and only a light-emitting diode emits during pulse duration, which is simpler (4).

A simple three-channel frequency multiplex system is shown in Fig. 4(a), which can be extended by adding more channels. Two channels are provided for nonelectrical quantities like temperature and pressure, and one for electrical values. Nonelectrical quantities are converted by transducers into electrical quantities (voltage). After necessary amplification, these signals modulate, a crystal os-

cillator by means of a varicap diode. The series resonant frequency of quartz crystal can be changed slightly (no more than $\Delta f/f_0 = 0.5 \cdot 10^{-3}$) by changing the capacity of the varicap diode by the measured voltage as shown in Fig. 4(b). Each oscillator oscillates on a different frequency $f_{01}$, $f_{02}$, $f_{03}$ so that multiplexing by frequency division is realized (5). The oscillators' output over the antenna coils are summed and transmitted over a common antenna. Instead of using varicap diodes, a voltage-controlled multivibrator can be used as the subcarrier, as shown in Fig. 4(c).

Multichannel transmission is often used in electroencephalography, but different physical values like heart potentials, temperature, respiration, and miography can also be measured simultaneously (5). Multichannel telemetry is also applied in telemetry by gait analysis (i.e., in each case even more different values must be transmitted simultaneously). With respect to energy saving, time multiplexing is preferable especially if the low-duty cycle can be obtained (6).

In this regard pulse position modulation is most promising, because only two pulses are required to restore an amplitude (Sync. pulse is not included). Using PCM for 8-bit quantization, four pulses are required on average, which means that twice as much energy is consumed and even more is used for 10- or 12-bit quantization. PWM is less accurate because of the possibility of pulse shape distortion, which may occur in long-distance transmission.

In Fig. 5(a) a transmitter using PFM is shown. The pulses at the output drive IR-emitting diodes if infrared (*IR*) biotelemetry is used; however, an HF oscillator can also be modulated in on-off key mode. This telemetry system is used for force measurement in legs and crutches

**(a)**



**(b)**



**(c)**
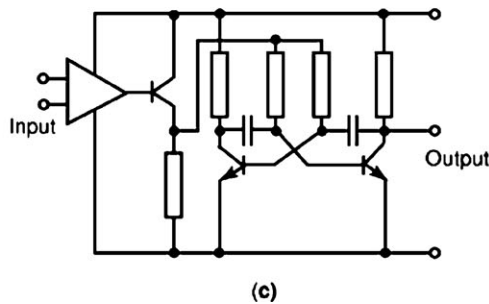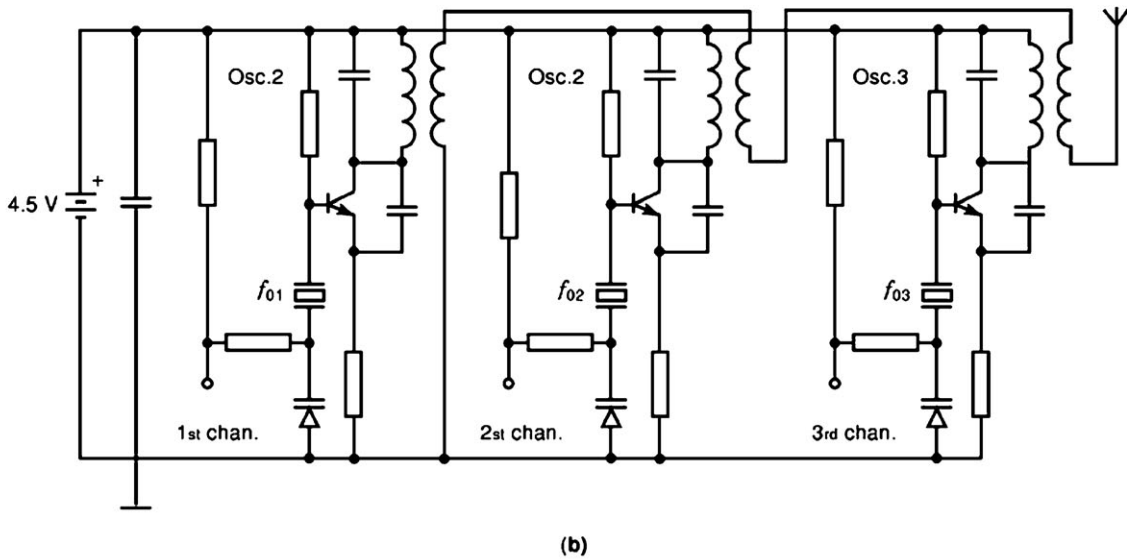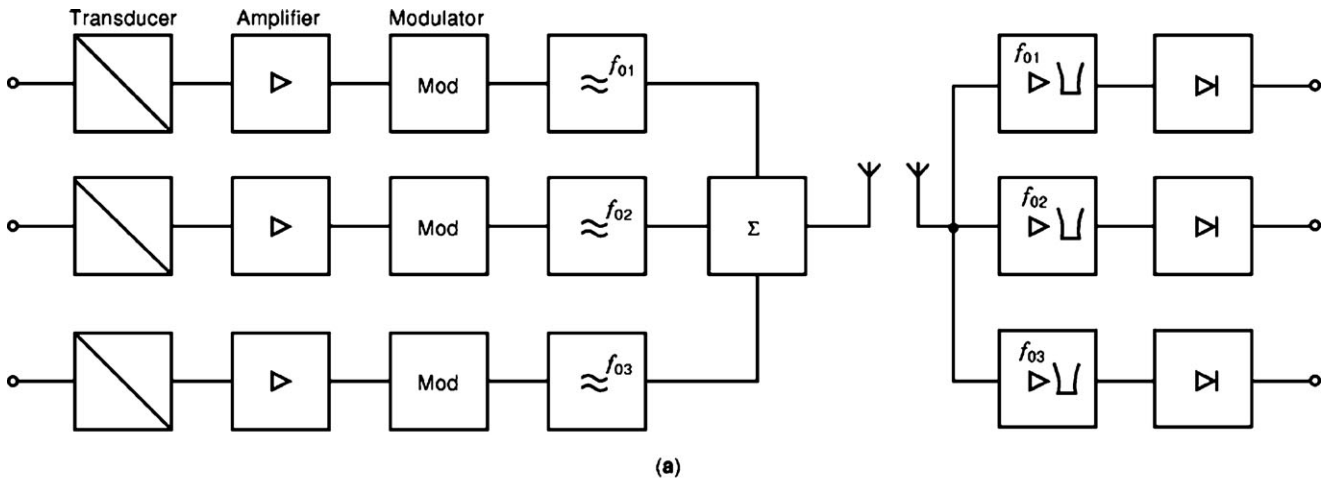
**Figure 4.** (a) Frequency division three-channel multiplex, (b) three-channel FM transmitter, and (c) voltage-to-frequency converter with multivibrator.

and has six force transducers in the input (6). The signals from the transducers are amplified and fed into the multiplexer (*MUX*). A clock circuit controls a series of binary-coded pulses which are sent to pins A, B, C through a counter. These inputs to the multiplexer sequentially select the channel (1, 2, 3, 4, 5, 6) to be connected to the comparator. The central unit also sends the pulses from the clock to a monostable multivibrator MM1, which sends the start pulse to the transmitter output stage and also starts the ramp voltage. When the voltage for a selected channel is equivalent to the ramp voltage, the comparator sends the second pulse. We define $\Delta t$ as the time interval between proportional to the measured voltage. After this, the multiplexer chooses the next channel, and the proce-
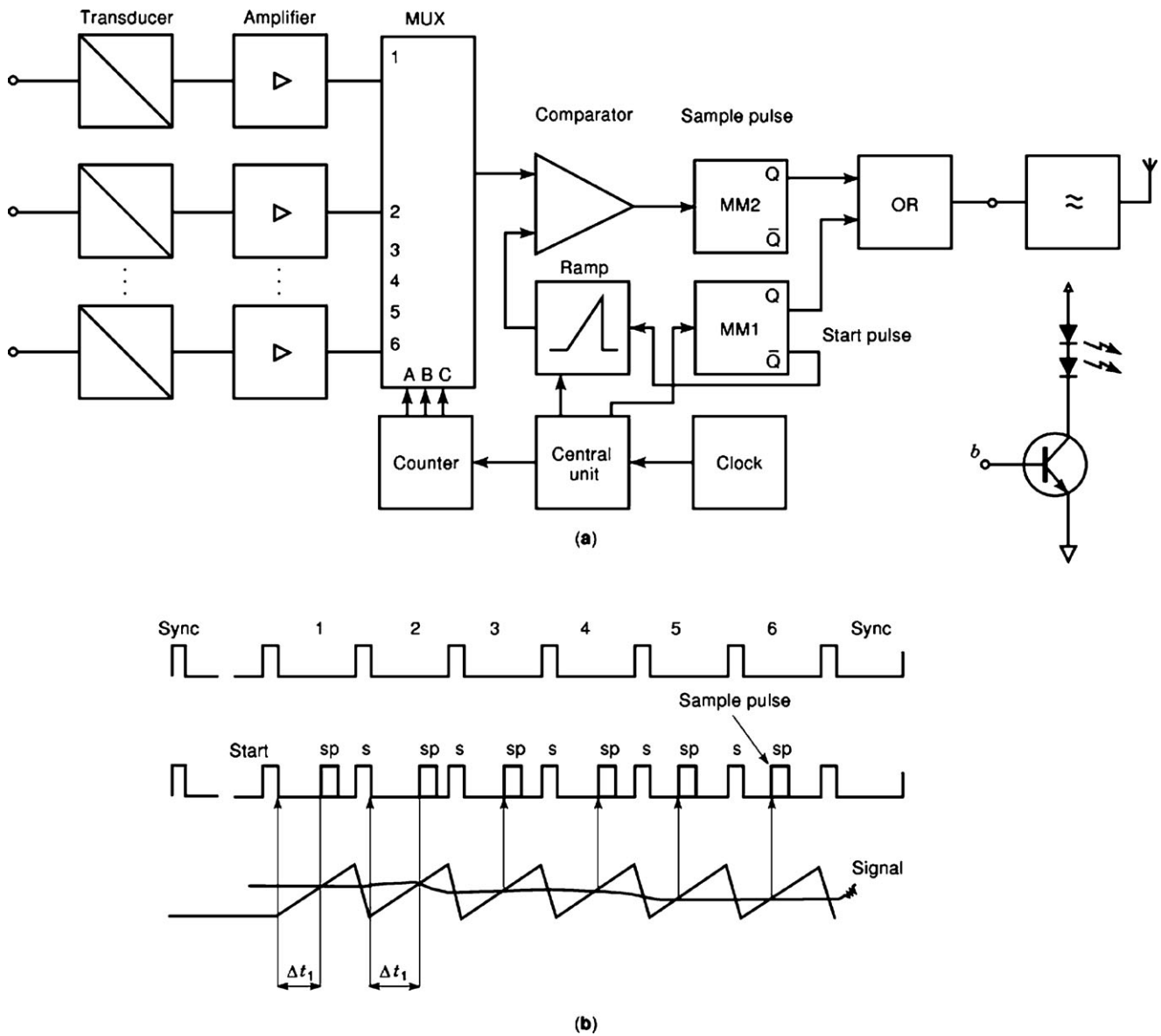
**Figure 5.** (a) Six-channel transmitter with PPM and (b) time diagram of PPM.

dure is repeated. In this way, pulse position modulation is realized. Each sequence of six channels is followed by a synchronization series consisting of seven pulses. The time diagram is shown in Fig. 5(b). The transmitted pulses can be infrared or HF signals. On the receiver side the signal is demultiplexed.

If frequency multiplexing is employed, the signal is transmitted continuously, as a sum of different frequencies, and in this case energy consumption is much greater.

## POWER SOURCES

### Primary Batteries

The power supply is a vital part of a biotelemetry system. It must have a high enough voltage so that one cell can power silicon transistor circuits and it must also have a high energy capacity, which is expressed in ampere-hours

(Ah). A high ratio between cell ampere-hours and weight is desirable. In the early days of biotelemetry, mercury cells, with an open circuit voltage of 1.35 V which remained almost constant to the end of the battery life, were mostly used. They had an energy density in the range of 100 Wh/kg to 125 Wh/kg, sustained voltage under the load, and low constant internal resistance. During their use, gas does not evolve. The chemical reaction of mercury cells is $Zn + HgO \rightarrow ZnO + Hg$. The mercury oxide (HgO) is the positive terminal, zinc (Zn) is the negative terminal, and potassium hydroxide is used as the electrolyte. There are also some other cells like zinc-manganese dioxide cells (or carbon-zinc), but they are very rarely used because of their large size and a low energy density of 55 Wh/kg to 77 Wh/kg.

Previously mentioned power sources cannot compete with lithium cells, which have gravity energy density up to 330 Wh/kg, nearly three times that of mercury and silver cells. They are composed of lithium (Li) as the neg-
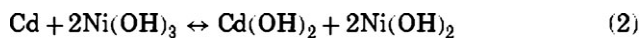
ative terminal and iodine (I) as the positive terminal. Lithium iodine (LiI) with polyvinil-piridin (P2VP) is used as a solid-state electrolyte, which provides some advantages with respect to battery life and high-temperature endurance, as well as a much higher voltage (2.8 V). Also, lithium–iodine cells have the highest volumetric energy density (600 Wh/dm$^3$). Their chemical reaction is

$$2Li + I_2 P2VP \rightarrow 2LiJ + P2VP \tag{1}$$

During the discharge process, lithium and iodine are turned into lithium iodine (LiI). This is the simplest reaction, but others are used in improved batteries with lithium compounds like lithium-manganese dioxide with 3.0 V open circuit voltage or lithium-thionyl chloride (SOCl$_2$) with 3.5 V. Also successful is the lithium-sulfur dioxide cell with 2.7 V open circuit voltage. Lithium batteries are currently the most used power sources in biotelemetry and pacemakers (7).

### Nickel-Cadmium Secondary Batteries

Nickel-cadmium batteries are the most commonly used batteries among secondary batteries (i.e., those that can be recharged repeatedly—approximately 500 cycles with 100% depth of discharge and 2000 cycles with 50% depth of discharge). Nickel-cadmium batteries have substantial advantages when compared with lead-acid secondary batteries because they can be produced in the sealed form since they do not generate gas during discharge. This make them appropriate for electronic equipment, including implanted biotelemetry circuits. They can be overcharged and have low internal resistance. However, when compared to the primary batteries, their energy density is low (only 40 Wh/kg) as is their voltage (1.25 V). Their chemical reaction goes in both directions, depending on whether they are charged or discharged

$$Cd + 2Ni(OH)_3 \leftrightarrow Cd(OH)_2 + 2Ni(OH)_2 \tag{2}$$

Cd is the negative terminal, and Ni(OH)$_3$ is the positive terminal. Ni–Cd batteries are manufactured as button cells or cylindrical cells. Button cells are more appropriate for small transmitters in biotelemetry. Cylindrical cells are adequate for large biotelemetry transmitters carried by patients where size is not restricted and multiple channels with higher energy consumption are required. Rechargeable batteries can be implanted inside an animal or human subject (some of the first pacemakers had rechargeable batteries) and can be recharged during the night, when the subject is sleeping, over the inductive coils (7).

Solar cells can also be applied or mounted on an animal's back, but rechargeable batteries are usually used to avoid voltage changes when the light changes intensity. Solar cells can also be placed beneath the skin, greater light intensities are available (2).

### BIOTELEMETRY APPLICATIONS

As already pointed out, the transmitter is the most important part of a biotelemetry system and usually requires the most sophisticated design. A transmitter including its power supply is always limited in size and weight and must be related to the size of the subject carrying it. If the transmitter is carried by a human, it might weigh up to 400 g, which permits multichannel signal transmission, as in the case of electroencephalography, when up to 16 channels can be transmitted, or in that of cardiology, when with three channels the patient can be tested under different activities during cardiac exercise tests. Multichannel telemetry is applied in gait analysis measuring forces in the legs (8), fetal heart energy examination, and in neurological cases where the patients with epilepsy can be followed up. In clinical multichannel telemetry, arterial blood pressure is often measured, as is respiration. Among the interesting data is body temperature during physical activities. Biotelemetry also enables measurements from relatively inaccessible regions like the stomach, small intestine and colon, where temperature, pressure, acidity (pH), and oxygen partial pressure are of interest (9). Of course, the patient should be unaware of the transmitter's presence. In this case, transmitters must be particularly small. For example, when investigating the intestines, the transmitters are usually swallowed and are called endoradiosondes or radio pills.

Endosondes can also be used for colon investigation and pressure measurement in the bladder, when introduced through the urethra. The similar endoradiosonde can be applied into the same places in animals as in humans.

In some cases with humans, it is necessary to measure some internal variables like pressure, temperature, or acidity in intestines, stomach, or colon when endosondes are swallowed or implanted after a surgical procedure. A dolphin can swallow a whole fish in which a temperature transmitter is positioned in the gill (2). For measurement purposes in humans, implantation is avoided except for electrostimulation. For animals, surgery is often preferable because the animal cannot pull or pick the transmitter from the location. A few days after surgery, the animal is recovered and does not feel discomfort. At this point, measurements can commence. Implanted telemetry can also be applied on animals in zoo exhibits (2).

In animal tracking, the same values are usually measured as in humans; however, some special values depend on the biologist's particular interest. Here, not only must the size of the transmitter be related to the size of the animal, but the transmitter must also be adjusted to the environment. For terrestrial animals, birds, and marine mammals, which rise to the sea surface to take a breath of air, RF electromagnetic waves are used exclusively. Consequently, among marine mammals, dolphins are tracked most often, but penguins, sea lions, and whales, among others, are also tracked. The transmitter is switched on only when they are on the surface. Biotelemetry is also applied to birds to examine the significance of their voice and singing (10), acceleration, and the power applied during the flight by measuring oxygen O$_2$ consumption. Because the birds can soar, distances over 50 km can be spanned. However, animal-ecologists and zoographers are most interested in studying bird homing and migration phenomena and tracking the birds in their daily life (1, 2). Biologists are also interested in tracking terrestrial animals like bears, wolves, and deer as well as different sorts of turtles in order to trace their mi-

gratory routes. Tracking also can be performed on rabbits, cow elk, and horses, to name a few. This kind of tracking is called wildlife tracking. To study fish, which never come up to the surface of the sea, ultrasonic transmitters must be applied. The ultrasonic receiver is connected to an RF transmitter floating on the sea surface. It receives sonic signals and transmits RF signal farther away as a relay. Sonic signals may be transmitted over distances of 10 m to 20 m to more than 2 or 3 km if the animal is large enough to carry a bigger transmitter, which is described later in more detail in the wildlife tracking section.

## TRANSMISSION LINKS AND PROPAGATION

In biotelemetry, most applicable transmission links are realized by electromagnetic waves in the radiofrequency range or in so-called RF biotelemetry. Also, electromagnetic waves in the infrared region with wavelengths from 0.8 $\mu$m to 1 $\mu$m are used in infrared (*IR*) biotelemetry. Ultrasonic transmission links are used least often. Ultrasonic transmission usually is applied to the aquatic animals because they live under the water. However, it is also used in a ranging system for gait analysis.

### Electromagnetic Transmission

Electromagnetic transmission covers almost all areas of biotelemetry applications. Biotelemetry practiced on humans has mostly clinical applications, but it has been used in sports by athletes and also in some vocations where strong physical activities are required, especially in hazardous environments (5).

In a biotelemetry system, most attention should be paid to the transmitter, because it is carried by the subject and should be made as small as possible. The receiver size is not limited.

The modulation modes were already described. Frequency modulation is usually applied on small, one-channel devices because it can be realized with simple circuits. Pulse (on-off key) modulation is applied mostly in all other cases, including multichannel systems.

The distance that can be spanned between the transmitter and the receiver depends on the strength of the electric field at the receiving antenna location, because the induced voltage $V$ in the receiving antenna is proportional to the receiving antenna effective length $h_{ef}$ and the electric field strength $E$ around the antenna

$$V = h_{ef} \cdot E \tag{3a}$$

$$h_{ef} = \frac{\lambda}{\pi} tg\pi \frac{l}{\lambda} \tag{3b}$$

When the antenna is a dipole with $l = \lambda/4$, the effective antenna length $h_{ef}$ is $\lambda/\pi$, where $\lambda$ is the wavelength of the transmitted electromagnetic wave, as shown in Fig. 6(a,b). This situation occurs when the transmitting antenna is either a dipole or a whip antenna ($l = \lambda/4$). The transmitting whip antenna is usually shorter than $l = \lambda/4$, in order not to be clumsy, which greatly diminishes the effective antenna length $h_{ef}$, which is proportional to $l/\lambda$, see Fig. 6(a,b). This situation occurs when the transmitting antenna is ei-

ther a dipole or a whip antenna ($l = \lambda/4$). The transmitting whip antenna is usually shorter than $l = \lambda/4$, in order not to be clumsy, which greatly diminishes the effective antenna length $h_{ef}$, which is proportional to $l/\lambda$, see Eq. (3b). The gain $G$, which is defined as the product $G = \eta \cdot D(\phi)$, where $\eta$ is the antenna efficiency and $D(\phi)$ the radiated power in the direction determined by $\phi$, drops faster than the $l/\lambda$ ratio according to the diagram in Fig. 6(c). The electric field $E$ on the receiving side depends on the input power $P_i$ and gain $G$ of the transmitting antenna and decreases with the distance $R$ according to

$$E = \frac{\sqrt{60P_i G}}{R} \tag{4}$$

This equation is valid if $R$ is longer than the wavelength for the far field. For the near field (distance $R < 0.2\,\lambda$), the electric field decreases by $R^3$. A whip antenna is usually used for the transmitter, whereas a dipole or long whip antenna can be used on the receiver where the antenna dimensions are not critical. Dipole antennas always have a span about 5% less than $\lambda/2$. To obtain better directivity, a dipole antenna has a number of metal rods, the so-called directors, which are 5% to 7% shorter than the dipole and located in front of the antenna and one or more longer rods (by about 5%) behind the antenna to act as reflectors. This type of antenna is called a Yagi antenna or array, [Fig. 6(d)]. In addition to the dipole, the loop antenna also has a directivity feature and may have one or more turns depending on the required inductivity. The $h_{ef}$ for the loop antenna is given as $h_{ef} = 2\pi \cdot n \cdot S/\lambda$, where $n$ is the number of turns and $S$ is the surface of the loop (Fig. 13). With high permeability, the directivity and $h_{ef}$ can be greatly improved if enough space is available. The loop antenna is also used exclusively for implanted transmitters or swallowed endoradiosondes because it can be made small. Usually the loop antenna or coil is the resonant circuit inductor of the endoradiosonde oscillator.

The transmitting frequency is usually determined by the size of the transmitter. If the size of the transmitter must be small, the transmitting frequency must be high. The oscillator resonant circuit of a small transmitter has small inductance $L$ and capacitance $C$, which determines the oscillating frequency

$$f_0 = (2\pi\sqrt{LC})^{-1} \tag{5}$$

The range of radiofrequencies used in biotelemetry lies usually between 27 MHz and 450 MHz. Because the transmitters are small, higher frequencies are preferred. Nevertheless, low frequency is required for underwater measurements, especially in well-conducting ocean water. The greatest possible in this case is given by an empirical formula

$$d = \frac{240}{\sqrt{f}} \tag{6}$$

where $d$ is measured in meters and $f$ is measured in hertz. We can easily see that when 50 kHz is applied, a distance of only 1.07 m can be spanned. The same is true of the implanted transmitter or swallowed endoradiosonde, because body tissue is just as highly conductive as ocean water. In
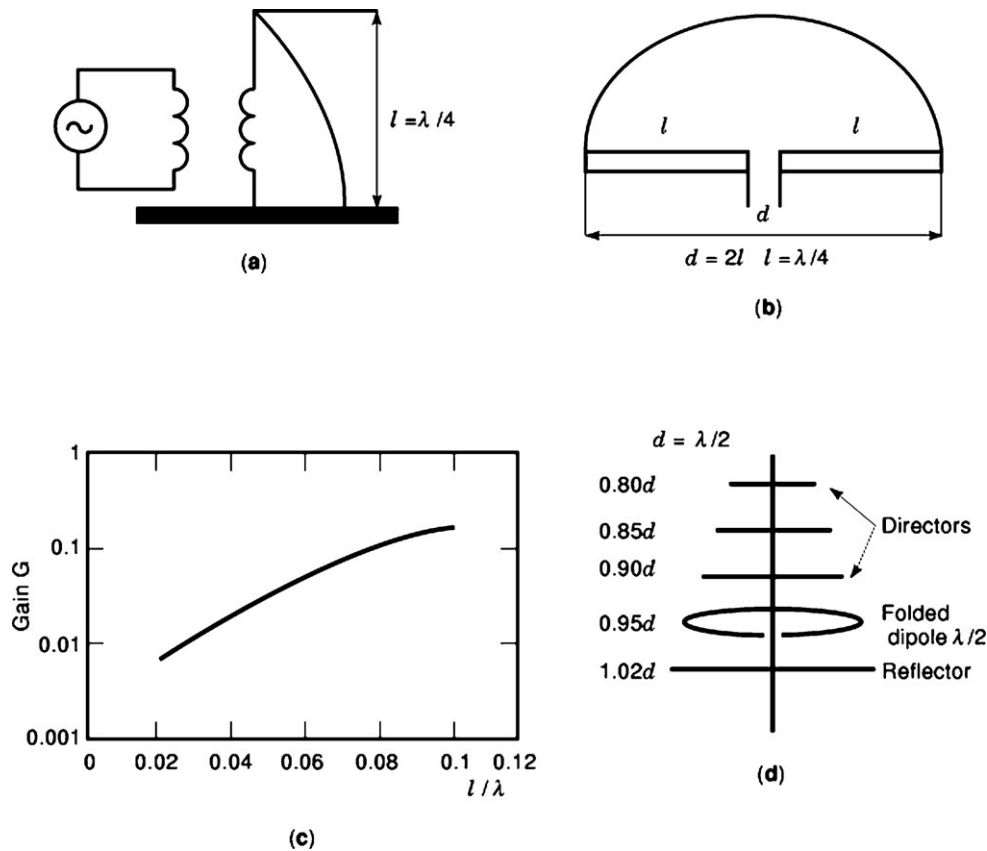
**Figure 6.** (a) Whip antenna, (b) dipole antenna, (c) antenna gain as function of $l/\lambda$, and (d) Yagi antenna.

this particular case, a compromise must be found between the size and the depth of body penetration. For telemetry inside the body, frequency modulation is used primarily in a range between 80 MHz and 400 MHz.

To obtain longer distances especially in free space, higher transmitting power is required. Consequently, HF power amplifiers must be employed.

**Infrared Diffuse Transmission**

Even though radiofrequency telemetry is exclusively used in open spaces, infrared telemetry has some advantages in enclosed spaces (4). Infrared biotelemetry is always working in an on-off key mode (i.e., mostly PPM or PCM in order to save energy). In this case, transmitters and photoreceivers are much simpler and do not require cumbersome antennas and coils for tuning. The mobility of a patient carrying a transmitter is complete inside the room, and there are no remarkable changes in the amplitude of the received signal. IR transmission shows almost no interference from other RF stations, power lines, or appliances. However, IR radiation is limited to the inside of an enclosed space. The space may be quite large when multiple receives are used and placed in the locations where the IR radiation is the weakest (8). The IR transmitter carried by a patient can be moved to other rooms and used in stairwells, halls, and wherever IR receivers are located.

To enable the user's unrestricted movement, the IR radiation must fill the whole room where the IR transmitter and receiver or receivers are located because of reflection by the walls. Because the wall roughness is greater than the IR wavelength, each ray $I_0$ from the transmitter is reflected at the wall in all directions according to the cosine law (Lambert's law) and Fig. 7(a),

$$I(\vartheta) = I_0 \cos \vartheta \qquad (7)$$

This type of IR biotelemetry based on reflection by the walls is called IR diffuse biotelemetry (4).

In Fig. 7(b,c) an IR transmitter and receiver is presented. The receiver is working in a current mode, which is most effective, but it can also work in a voltage mode. To improve the signal-to-noise ratio, more photodiodes in the receiver must be used, but a large number of photodiodes increase the capacitance, which limits the IR-receiver frequency range. However, an optimum exists between six and eight photodiodes (8).

The IR-diffuse telemetry range can be extended by using multiple IR receivers in locations where IR radiation is weakest. The output signals from all these IR receivers are connected to a summing unit where they are added. The summing unit with the amplifier is designed in such a way that if the signal from some receiver is too small, or does not exist at all, that signal and the noisy output of its receiver is eliminated from the summing unit.

IR telemetry is mostly used for patients in hospitals transmitting ECG or EEG signals. There are also applications in gait analysis for force measurement in legs and
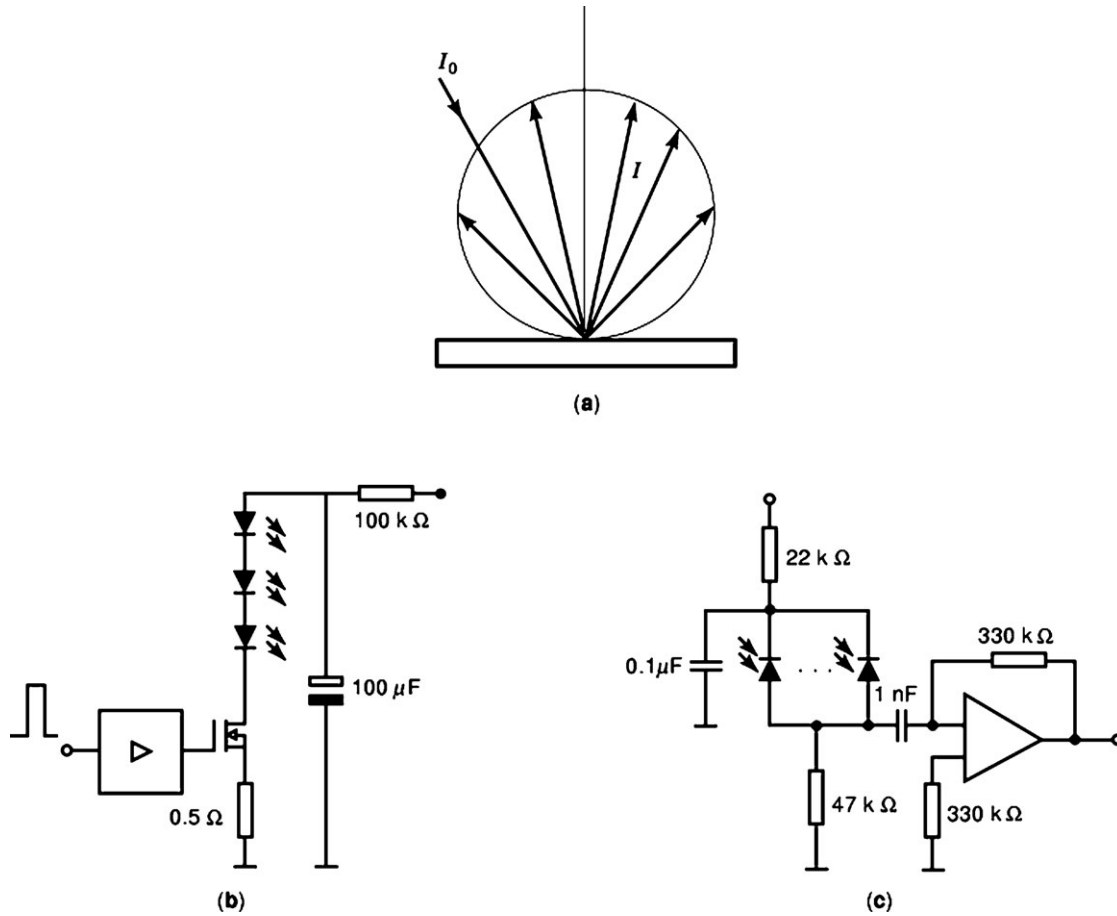
**Figure 7.** (a) IR diffuse reflection, (b) IR transmitter, and (c) IR receiver.

crutches (6, 8). IR telemetry is employed in the measurement of myographic potentials, temperature, and heart rate for sportsmen and athletes but only inside rooms where IR rays can be reflected.

### Ultrasonic Transmission

We have already shown in Eq. (6) that RF transmission is strongly attenuated in water, so that measuring aquatic animals in their normal habitat, where they enjoy free movement, is not possible. In this case, only sound signals at frequencies above the audible threshold can be used. Sound signals transmit very well in water. The transmitting frequencies are usually low, between 50 kHz and 200 kHz, and the distances that can be spanned by them do not exceed 200 m. The emitted power is usually not higher than 1 W/cm$^2$ (2, 3).

The conversion of electric energy into mechanical energy is done by piezoelectric ceramics like lead-zirconate-titanate. This material has a dual behavior. When a force $F$ is applied on a disc of piezoelectric material, a charge $q$ is induced on its electrodes according to $q = \alpha \cdot F$ (where $\alpha$ is a constant), as shown in Fig. 8(a). Because there is a capacitance $C = \varepsilon_0 \varepsilon'(S/d)$ between the electrodes, where $S$ is the area of the electrodes and $d$ the thickness of the ceramic, a

voltage $V$ is induced according to the relation $q = C \cdot V$,

$$V = \frac{\alpha \cdot F}{C} = \frac{\alpha F}{\epsilon_0 \epsilon' S} d \tag{8a}$$

or

$$E = \frac{\alpha}{\epsilon_0 \epsilon'} \sigma \tag{8b}$$

Also, from the Eq. (8b), where a stress $\sigma = F/S$ is induced by the electric field $E = V/d$

$$\sigma = \frac{\epsilon_0 \cdot \epsilon'}{\alpha} \cdot \frac{V}{d} \tag{9}$$

In this case, the stress $\sigma$ in ceramic material changes the thickness $d$ in relation to the applied voltage $V$. This feature is used by the ultrasonic transmitter shown in Fig. 8(b). An oscillator oscillating on frequency $f_0$ can power a piezoelectric transducer that emits ultrasound. The frequency of the oscillator is usually adjusted to the resonant frequency of the piezoelectric ceramic to obtain the best efficiency. The oscillations are interrupted by a multivibrator or the oscillator that is working in the squegging mode (see the discussion in the next section). The frequency of these interruptions is controlled by a measured parameter like temperature or by an electrocardiogram. In Fig. 8(c), an ultrasonic receiver with a piezoelectric transducer and an
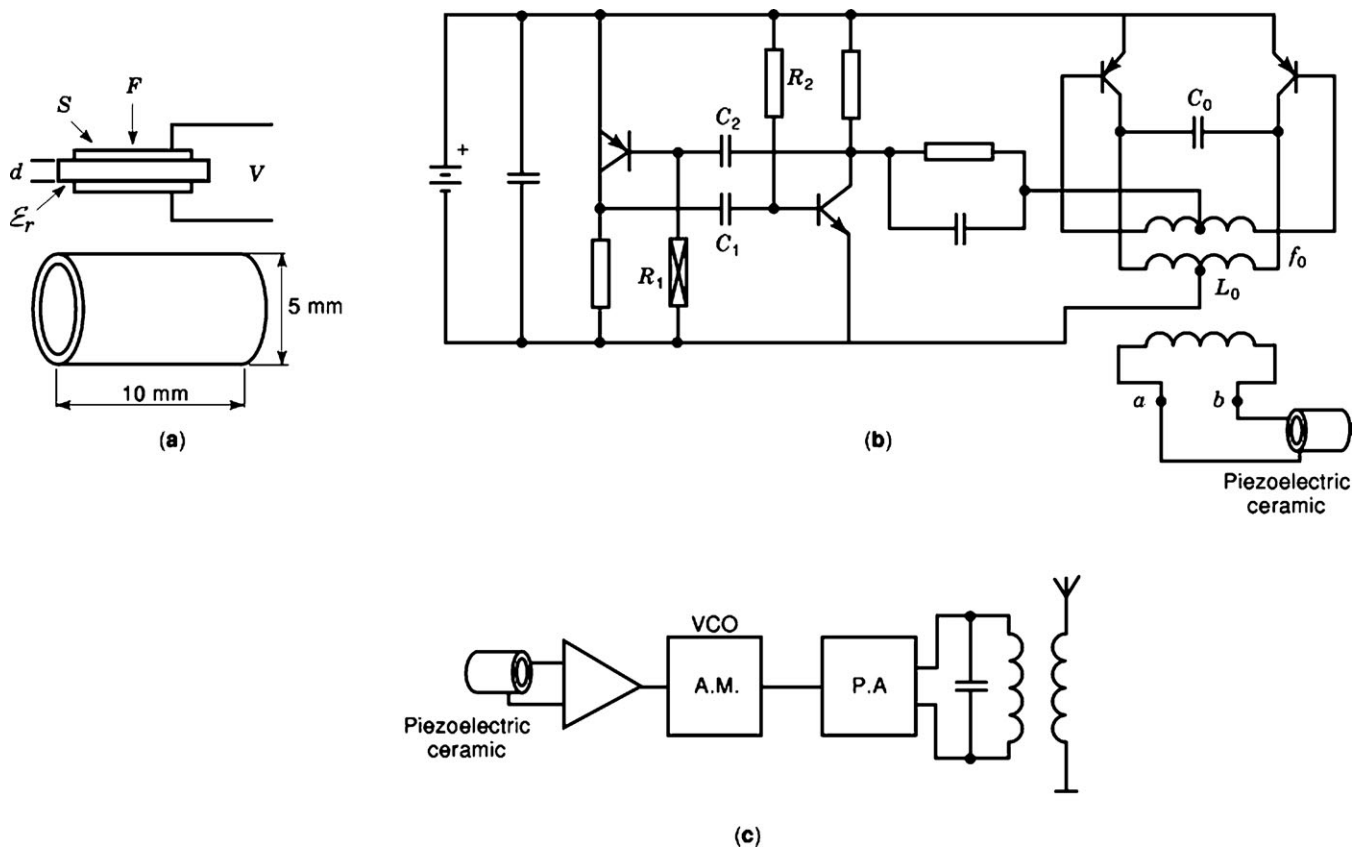
**Figure 8.** (a) Piezoelectric crystal, (b) ultrasonic transmitter, and (c) ultrasonic receiver.

HF transmitter as a relay station is shown. The ultrasonic signal, received from a transmitter on a fish, converted to voltage, controls the frequency (*VCO*) of an astable multivibrator (*A.M.*). Now this FM signal is amplified by an HF power amplifier and emitted by an antenna as an electromagnetic wave. This relay station is floating on the ocean surface. If the transducer is a disc, the ultrasound is transmitted in only one direction. To transmit ultrasound in all directions, a small hollow cylinder is used [Fig. 8(a)] (diameter of 0.5 cm and about 1 cm long). With this cylindrical transducer, spherical wave spreading is obtained, and sound intensity falls off proportionally to $1/R^2$. In shallow water where sound cannot spread in all directions, the intensity falls off by the $1/R$ law (3). Some dolphins are sensitive to frequencies up to 150 kHz, therefore the transmitted ultrasound frequency must be two or three times higher so as not to disturb them (2). Acoustic telemetry is also useful to divers for measuring heart and respiration rate and diving depth (11).

## ENDORADIOSONDES

Endoradiosondes are transmitting devices for measuring different variables within the body. They are either swallowed or noninvasively introduced into the bladder through the urinary tract or into the colon. Endosondes are mainly used for measuring pressure, temperature, or pH value (acidity) in the stomach and intestines. They also can measure biopotential with special sensors, especially

oxygen $O_2$ and, rarely, chlorine Cl. Endosondes can be active or passive. Active endosondes have their own power source. Today, lithium batteries are used mostly. Passive endoradiosondes or implants do not have their own power source and are powered from an outside source by coils. Endoradiosondes can also be implanted after a surgical procedure inside the human body to follow up some healing process. This type of endoradiosonde is passive, because it must dwell inside the body for a long time and small batteries do not store sufficient energy for such a long-term operation.

Endoradiosondes that are swallowed should be as small as possible—their largest parts are the batteries and coils. They are usually very simple oscillator circuits whose frequency $f_0$ is altered by the measured signal. This frequency modulation has low deviation $\Delta f/f_0$, not higher than 10%, but sometimes lower than 1%. In Fig. 9, transformer-coupled, Collpits, and Hartley oscillators are shown. These oscillators are usually applied in endoradiosondes. FM is the simplest modulation mode in one-channel biotelemetry. The transmitted signals are received by a loop antenna (up to 35 cm) located over the patient in a supine position. With smaller loop antennas that are only a few centimeters in diameter, endosonde tracking can be provided because of better directivity. Endosondes are primarily used for pressure measurement in the small intestine or bladder with inductive transducers. This inductance $L$ is at the same time part of the oscillator's resonant circuit that determines the oscillation frequency $f_0$ according to Eq. (5).
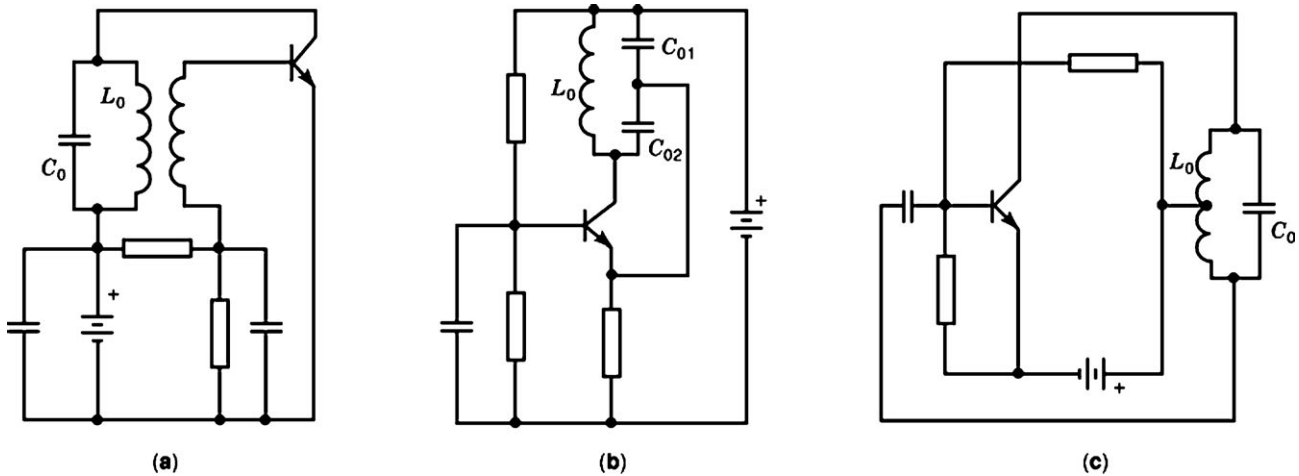
**Figure 9.** Oscillators: (a) transformer-coupled, (b) Colpitts, and (c) Hartley.

The change of the oscillator frequency $f_0$, which is caused by a change in inductance $L$ or capacitance $C$, can be expressed by partial derivatives,

$$\frac{df}{f} = \frac{1}{2}\frac{\partial L}{L} + \frac{1}{2}\frac{\partial C}{C} \tag{10}$$

According to this formula, 20% change in inductance $L$ or capacitance $C$ yields a 10% deviation in oscillation frequency. For pressure measurement, the simplest solution is to change the inductance $L$ of the coil by moving a ferromagnetic core inside the coil. The core is connected to a membrane whose displacement is proportional to the outside pressure. This is depicted in Fig. 10. The inductance of the coil can be changed by air gap displacement as well.

For temperature measurement, a temperature sensitive capacitor $C(t)$ that changes the oscillating frequency is used. Temperature can be measured using a thermistor (a very sensitive temperature resistor), which determines the frequency of the intermittent oscillations of a squegging oscillator. Squegging oscillators have strong positive feedback and a large time constant $RC$ in the base circuit of the oscillator transistor. When the oscillations start increasing and reach saturation, the oscillator feedback factor ($\beta A$) becomes low, and the oscillations start to decrease to the end. The time constant $RC_1$ defines the time when the next oscillations will start. In this way, the period between two subsegment oscillations $\Delta t$ is proportional to the $RC_1$ time constant. The squegging oscillator is shown in Fig. 11. This type of oscillator is also used to determine the temperature of the human brain on the durameter following a surgical procedure, where resistor $R$ is a temperature-sensitive sensor (thermistor) (2). The thermistor $R$ controls the frequency of an astable multivibrator, which keys the HF oscillator. In this way, we can measure the temperature in women during their menstrual cycles and neonatal mesal air flow for apnea monitoring (12).

The acidity which is often measured in the intestines and stomach is defined by the pH value, which for acids is between 1 and 7. For hydroxides the pH value is between 7 and 13. The pH value is defined as pH = −log [H⁺]. Using special electrodes, we can measure acidity as the potential difference $\Delta V_H$ between them. One of the electrodes, the so-called glass electrode, is made of a thin glass membrane that permits the passage of only hydrogen ions, and the obtained voltage difference $\Delta V_H$ on the glass membrane is proportional to the pH value given by the Nernst equation:

$$\Delta V_H = -2.3\,\frac{RT}{nF}\,\log\frac{[H_1^+]}{H_2^+} \tag{11}$$

Here $R$ is the gas constant, $T$ is the absolute temperature in degrees Kelvin, $F$ is the Faraday constant, $n$ is the valence, $[H_1^+]$ is the measured concentration of hydrogen ions outside the glass membrane, and $[H_2^+]$ is the concentration of hydrogen ions inside the membrane, which is close to 1 (or pH = 1). Substituting all these constants into Eq. (12),

$$\Delta V_H = -0.198(273 + t)\cdot\text{pH} \tag{12}$$

where $t$ is the temperature in °C of the solution and $V_H$ is measured in millivolts. The second electrode is a reference electrode with a constant potential $V_r = 0.2424$ V, which is not influenced by the outside H ion concentration. The reference electrode is usually made of calomel ($Hg_2Cl_2$), so that the measured voltage differences $\Delta V_H$ in Fig. 12(a) (13, 14). The electrodes are placed on opposite sides of the endosonde, and the voltage $\Delta V_H$ between them is applied to the voltage-sensitive capacitor or varactor ($p$-$n$ diode), which is also the capacitive arm of the resonant circuit. In this way, it changes the oscillator frequency. The transmitter circuit with amplifier and an astable multivibrator as oscillator is shown in Fig. 12(b).

## PASSIVE IMPLANTED TELEMETRY DEVICES

The largest components in all implanted electronic devices are the battery and inductive coil. If the device must remain inside the body for a long time, the size of the battery is the main obstacle to implantation. Passive devices have no battery, and energy is supplied to them externally from a battery source through the skin and other tissue. The magnetic field created in an external coil $L_1$, usually called the energizing coil, induces a voltage in the implanted coil
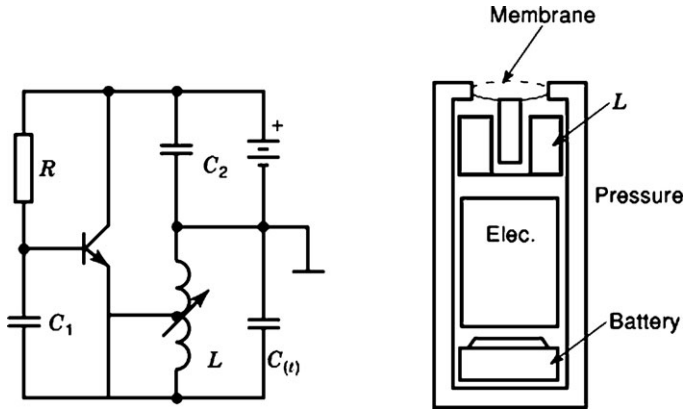
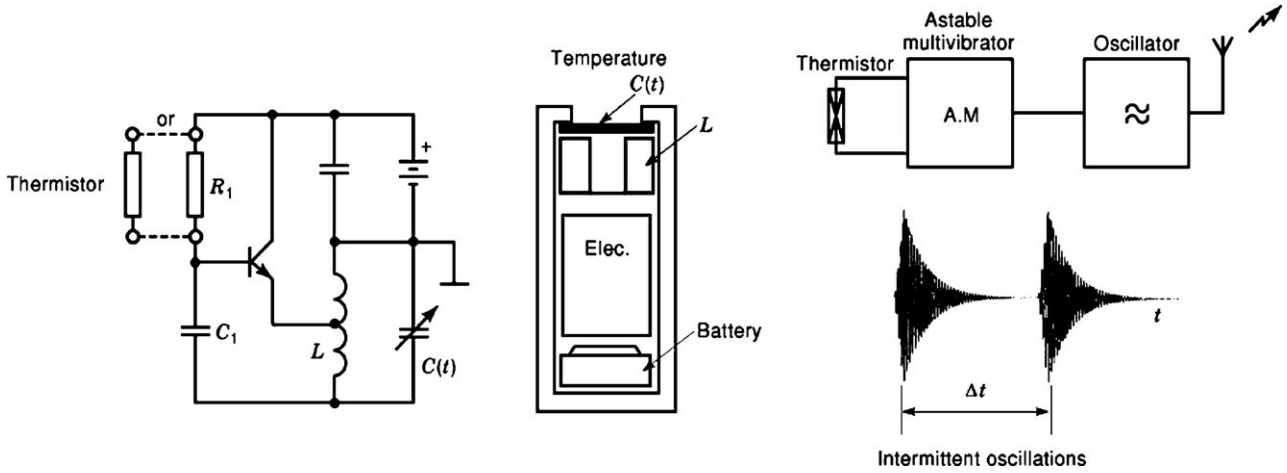**Figure 10.** Endoradiosonde for pressure measurement.



**Figure 11.** Endoradiosonde for temperature measurement with temperature-sensitive capacitor $C(t)$ or thermistor.

$L_2$ as shown in Fig. 13. To avoid interference with the power supply frequency $f_p$, the external coil $L_1$ takes energy from a power amplifier and oscillator at a frequency that differs from the implanted transmitter's oscillator frequency $f_s$, which transmits the measured data. However, the power amplifier and transmitter usually work at different times. The power oscillator charges the capacitor $C_p$ for a period of time and then stops emitting energy at which point the transmitter sends data on the frequency $f_s$ (15). The external coil can also be used to control an implanted stimulator.

The HF voltage induced in the receiving coil is rectified to obtain direct current, which can power the implanted data transmitter. The rectifier can be connected as a voltage doubler [Fig. 14(a)] or a full-wave rectifier, as shown in Fig. 14(b). In Fig. 14(a), a temperature-measuring FM transmitter is powered by the rectifier with a temperature sensitive capacitor $C$ in a resonant circuit. The energy can be transmitted continuously or with interruptions. The maximum energy will be transmitted when the coupling factor $k$ is high; it will also transmit $Q_1$ and receive $Q_2$ resonant circuit quality factors. Here $L_1$ and $L_2$ are inductivities of the energizing and receiving coils (Fig. 13). The efficiency factor $\eta = P_2/P_1$ between received power $P_2$ and

transmitted power $P_1$ can be calculated by

$$\eta = \frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2} \qquad \text{where } k = \frac{M}{\sqrt{L_1 L_2}} \qquad (13)$$

If the value $k^2 Q_1 Q_2$ is much greater then 1, the efficiency is approaching 100%. However, in practice, this value cannot be realized; consequently, the optimal efficiency is not better than 20%. The value $k^2 Q_1 Q_2$ can be written as

$$k^2 Q_1 Q_2 = \frac{\omega^2 M^2}{R_1 R_2} \text{ where } Q_1 = \frac{\omega L_1}{R_1} \text{ and } Q_2 = \frac{\omega L_2}{R_2} \qquad (14)$$

Here the resistances $R_1$ and $R_2$ include losses in the transmitting and receiving coils as well as the capacitors $C_1$ and $C_2$. Mutual inductivity $M$ depend on the distance between coils $L_1$ and $L_2$. Both coils, $L_1$ and $L_2$, and capacitors $C_1$ and $C_2$ are resonant circuits tuned to the same frequency $f_p$ (5). The implanted circuit can last for more than one year. For example, after a hip operation, tissue transplant rejection or tumor development can be monitored by measuring its temperature. Also, after brain surgery of the hydrocephalus, measurement of intracranial pressure might warn of impending danger. Besides taking measurements, electromyographic potential could be transmitted to control an artificial limb or strain gages could be used to monitor the forces in massive orthopedic implants (16, 17). Pas-

sive implanted devices are applied for relative strain measurements with strain gages hermetically sealed in the bone cavity for monitoring fracture healing. Also, the temperature increase in an artificial joint at the hip or knee can be monitored (17).

Some stimulators, like the cochlear stimulator (an implant for the deaf) use telemetry for measurement of stimulus amplitude and pulsewidth of any of its 16 control leads. This implant receives energy via an external coil (18). Figure 15 shows a demodulated signal taken by an endoradiosonde for acidity measurement. It shows the pH value in a healthy man, which changes after taking 0.5 g $NaHCO_3$ before and after breakfast.

Note that some implanted devices (even nonpassive) also have small rechargeable cells (mostly Ni–Cd), which can be recharged with magnetic coils when necessary. In this way, the transmitter can work continuously.

## ACTIVE IMPLANTED TELEMETRY DEVICES

Active implanted telemetry devices are powered by the battery. The telemetry transmitter is made up by a frequency (FM) or pulse coded (PCM) oscillator modulated by measured signals and a power-amplifier with a resonant circuit tuned to the oscillating frequency. The inductance of resonant circuit is made as a coil which serves as a loop antenna in this case (Fig. 9). In most cases the telemetry circuits are a small part of a composed implanted device such as a pacemaker or stimulator. Programmable pacemakers or stimulators are mostly controlled by RF-pulses via inductive coils outside and inside the body as is shown in Fig. 13 for energy transfer. Inside the body is the receiving coil as a resonant circuit, which receives control pulses, which is not telemetry. Some pacemakers have also telemetry for sending measured data in an opposite direction from the control pulses over the same transmitter coil used for receiving the control pulses, but in a different time interval. That information can be stimulating the pulse amplitude and duration or the battery's internal resistance to predict its end of life. Also, stored data of heart beat rate or an electrocardiogram can be transmitted. The modulation type most used is the amplitude on-off pulse modulation or frequency modulation with carrier frequency between 30 kHz and 175 kHz. Pacemaker telemetry transmitter is switched on only to send required data and can be activated over a receiving coil by coded RF-pulses or by a reed-relay built into the pacemaker which is responding via magnetic pulses or permanent magnet.

For fetal studies before and during birth, a transmitter with coil for multichannel transmission of fetal ECG and heart rate can be used. In some cases also brain voltage (EEG) can be transmitted by telemetry. This contactless telemetry measurement is more convenient than if the electrodes are placed on the maternal abdomen where interference between maternal and fetal ECG usually occurs. In this case frequency modulation (FM) is applied, or FM–FM modulation for multichannel transmission. These measurements are performed on the fetuses of dogs, sheep, or monkeys, and even dolphins (2).

Biotelemetry is also used for monitoring the rejection of heart transplants based on analysis of intramyocardial electrograms. This method is noninvasive in comparison to the frequent endomyocardial biopsies. Acute heart transplant rejection can be estimated from an intramyocardial electrogram and ventricular evoked response with the same electrodes employed for heart stimulation and for sensing this biopotential (19).

## TRANSPONDERS

A transponder is a transmitter that sends a high-frequency pulse, when it is triggered by a pulse from a sensitive continuously active receiver associated with the transmitter. When the information from a distant measurement transmitter is required, a pulse from the researcher's location is sent. The receiver triggers the transmitter to send the required data over a monostable multivibration. The receiver's circuits are similar to those of the passive implanted transmitters, except that the receiver is continuously powered by the batteries and the transmitter only when it is required by the pulse from the receiver. A block diagram of a transponder is shown in Fig. 16. The transponder is usually located on the animal from which data are being collected. The transmitter uses a whip antenna. The animal can either carry the transponder on a collar around the neck or have it implanted for long-term temperature measurement, as in pigs (20). In this case the transponder is made as an active implanted device.

The transponder can also be used for distance measurement between the animal carrying the transponder and the transmitter at the researcher's location. The transmitter sends an HF pulse that is received by the transponder's receiver and triggers a monostable multivibrator over which the transmitter returns the HF pulse, but on a different frequency $f_t$ than the received frequency $f_r$ at the researcher's location. The time interval $\Delta t$ between leading edges of the sending and receiving pulse is proportional to twice the distance $2d$ between the animal and the researcher, which when multiplied by the electromagnetic wave velocity $c$, gives distance $d = (c/2)\Delta t$. The transponder can be adjusted so that as soon as the receiver receives the pulse from the transmitter of the transponder, it sends the new pulse. The whole system then becomes self-oscillating, and the frequency of this oscillation is inversely proportional to the distance (2).

Booster transmitters are relay stations that extend the range of transmission. If a weak signal from an endosonde cannot be received far from the body it is monitoring, the receiver of the booster transmitter receives this weaker signal, amplifies it, and transmits it by a more powerful transmitter to reach over a greater distance. The frequency of a transmitted signal must be different from the frequency on which the receiver is tuned to avoid positive feedback.

## PACKAGING

Packaging is of great significance for implantable electronics. Body fluids and moisture ingress can short-circuit implanted electronic circuits. The polymers most used for
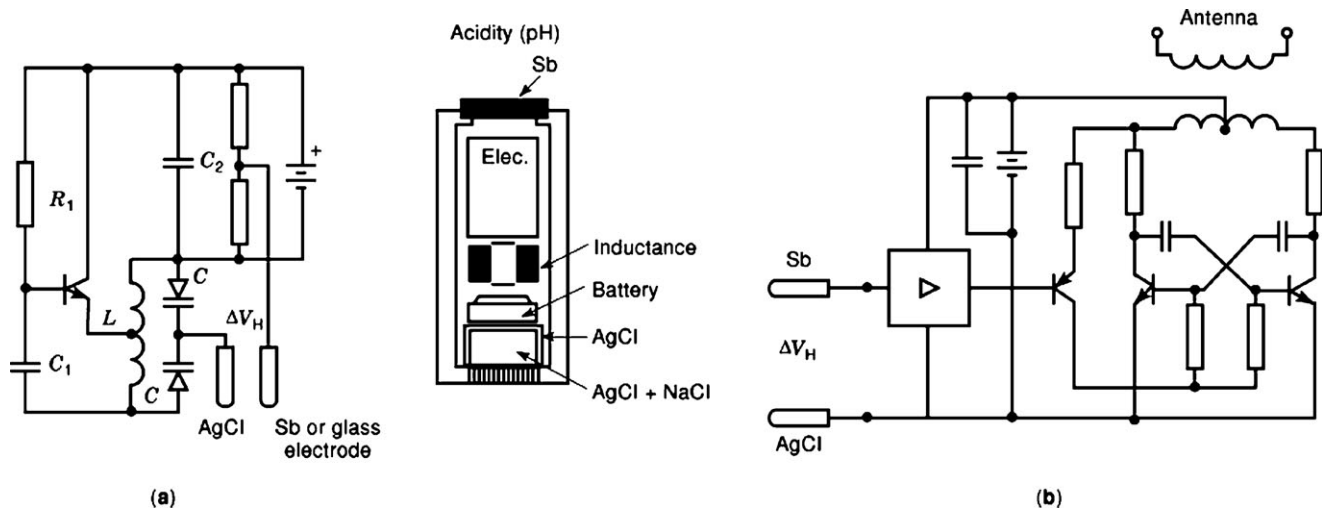
**Figure 12.** Endoradiosonde for pH-value measurement with (a) varactor and (b) astable multivibrator as voltage-to-frequency converter.
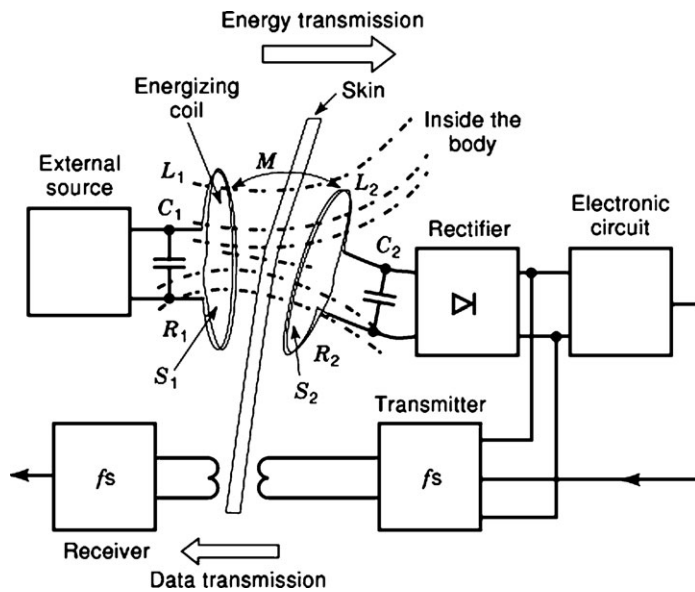


**Figure 13.** Energy and data transmission by electromagnetic coupling.

packaging are epoxy or silicon rubber. Epoxy is convenient for coil encapsulation because, as a nonconducting material, it does not significantly attenuate the power transmitted by the coil. However, metallic packing, mostly made from titanium and its alloys, enables hermetic sealing of built-in electronic circuits, but as a conducting material it absorbs the RF power of the transmitting coil, which is therefore usually placed outside the titanium package. In this regard, ceramic material recently developed, enables hermetic sealing of the transmitting coil and, as a nonconducting material, it does not permit creation of eddy currents and power attenuation in the transmitting coil. Due to the high packing density, it is possible to integrate all analog and digital sophisticated functions of a pacemaker onto about a 4 mm × 4 mm silicon chip. In the telemetry transmitting devices this technology can be applied using hybrid or surface-mounting technology (*SMT*) to make connections between monolithic and passive components. Usually electronic circuitry is surrounded with the trans-

mitter coil which with the battery, if it is used, takes up most of the available space in the implant.

## WILDLIFE TRACKING

Of great interest to biological scientists is the study of homing and migrating birds and terrestrial and marine animals. In this regard, telemetry offers unbeatable advantages in conveying the position of freely moving animals in their normal unrestricted environment without any disturbance. At the same time, additional data can be collected from the animal (temperature, heart beat) as well as the environment. To fulfil this requirement, the scientist must know the exact location of the animal at any given time including its direction of travel, so that he can plot its position on a map.

To accomplish this task, the animal must be tagged with a transmitter that emits a coded signal or that operates on a particular frequency that identifies the animal. The ra-
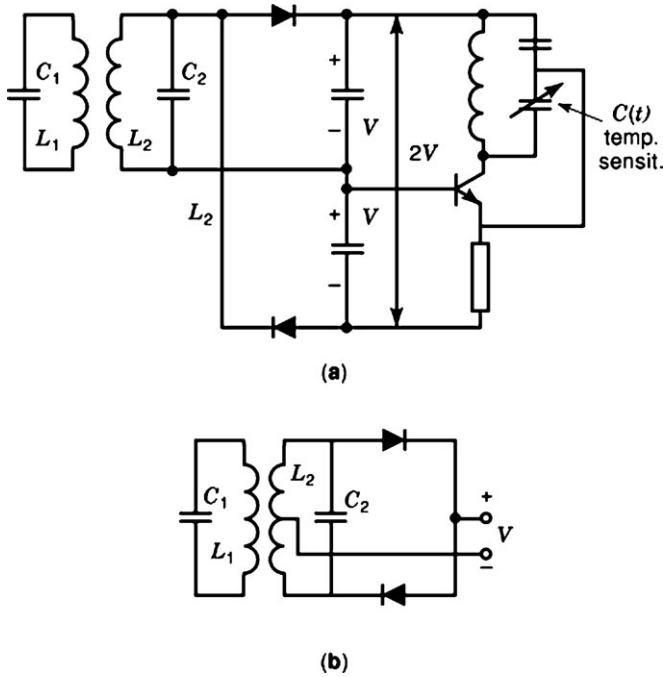
**(a)**



**(b)**

**Figure 14.** (a) Rectifier with voltage doubling and (b) full-wave rectifier.

dio transmitter carried by the animal has usually a vertical whip antenna that radiates electromagnetic waves in all directions. The receiving antenna must be a directional antenna that has maximal gain in the direction in which the transmitter is located and that is determined by azimuth angle. This can be a multielement (three to five directors and a reflector) Yagi antenna or a loop antenna (see section entitled "Electromagnetic Transmission"). The transmitter frequency for a Yagi antenna with reasonably long elements must be about 150 MHz. By rotating a directional antenna at the researchers location $A$, a maximum receiving signal must be found, as must the azimuth angle in which direction the animal is located. The maximum receiving signal can be found with earphones or a pointer-scale indicator. To find the accurate position, a second receiver with a directional antenna must be located at some other place $B$. When a maximum is found at this place and the azimuth angle is determined, two straight lines from $A$ and $B$ are plotted in the direction defined by the azimuths. Their intersection is the location of the animal, as shown in Fig. 17.

However, using this method to determine this location is not very accurate, because the error in the azimuth angle may be as large as 5°. It is also possible to receive reflected signals on some hilly terrain. In this case, another location $C$ must be used, and the systematic error needs to be analyzed by testing the triangulation system (21). See Fig. 17. It is easier, but less accurate, to find the location of the animal with only one receiver, which can find the direction, and a transponder as the range-measuring instrument. Refer to Fig. 16 for more details. The distance to be spanned depends on the transmitter's output power carried by the animal. Also, the spanned distance is dependent upon the altitude at which the animal is located. Tracking birds that are flying high or sitting on a tree requires that much longer distances be spanned. For example, a trans-
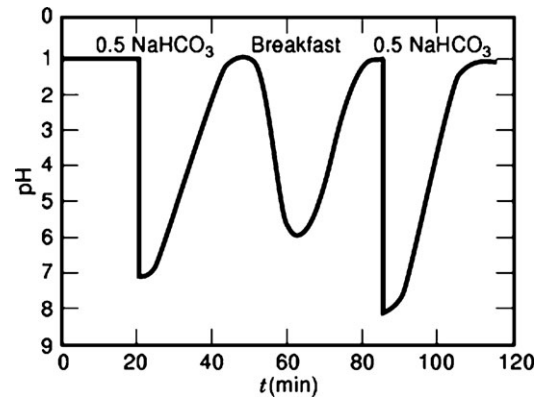


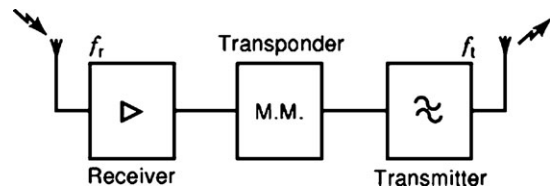**Figure 15.** The pH value changes during the breakfast and NaHCO$_3$ taking.



**Figure 16.** Transponder.

mitter carried by an animal and having a 0.1 W output power on the ground can achieve a range of 200 m. When the animal climbs 3 m up into a tree, the measured distance is nearly 4 km. Distances that can be spanned are usually in a range of from a few hundred meters to about 50 km (19).

Much shorter distances can be spanned when permanent magnets or radioactive markers are used instead of battery-powered transmitters. For detecting these tags, sensitive magnetometers or radiation meters must be used.
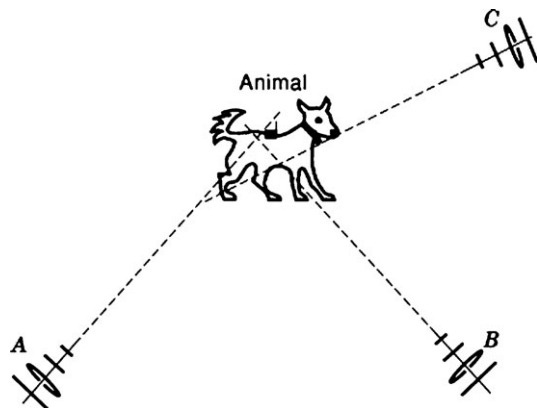
**Figure 17.** Animal tracking by directional antennas.

Magnetometers mostly employ Hall-effect sensors, or inductance detectors. Radioactive iodine can be used as the radioactive marker. These tags are mostly intended for short distances and small animals.

Today Global Positioning System (*GPS*) is employed more and more for animal tracking. It allows scientists to obtain the location of the animal with high accuracy (within 25 m). GPS uses 24 satellites 20,183 km above the earth's surface and provides 24 h coverage of the entire planet. The satellites work on two *L*-band frequencies (1575.42 MHz and 1227.6 MHz). The GPS users on earth have access to at least four of the satellites. The GPS tracking system consists of an animal-carried GPS receiver and transmitter, which is produced by many manufacturers (22, 23). The built-in microcontroller periodically (usually every 3 s) turns on the GPS receiver to get a position from the satellite. The GPS receiver computes its position and puts this information into RAM in the control unit. Then the GPS receiver is switched off and the RF transmitter is turned on in order to transmit these data via a digital telemetry link to the data-logging computer system at the remote researcher's site, as shown in Fig. 18. Automatic data recording is possible by computer, and a mapping program displays the information on the monitor. GPS gives the latitude, longitude, and elevation of the animal's location. The accuracy within 25 and 40 m can be significantly improved using a differential technique, the so-called differential GPS (*DGPS*). DGPS can obtain accuracies within 0.5 and 5 m, but it requires a stationary GPS receiver at a known location (reference station) to send corrections to the mobile receiver. Neither the DGPS technique nor the real-time kinetic (*RTK*) GPS system, which is even more accurate in the centimeter range, is in wide use.

The Argos System is older and is less accurate than GPS. The Argos system, however, employs two satellites that circle the globe at a lower altitude (850 km) seven to eight times a day. The transmitter carried by the animal sends the coded signal to the satellite, which responds to it giving its coordinates. The transmitter can be made small, but its accuracy is low—between 150 m and 1 km. For example, the Argos system application is used in the migratory study of dolphins. The transmitter works only when dolphins stay near the sea surface (0.75s). It has a 2 W power output on 400 MHz and weighs 1.4 kg. The battery life span is 1200 h (24).

Satellite communication is, except in wildlife telemetry, applied in emergency medicine from a moving vehicle to a satellite using mobile satellite communications and then from the satellite to a fixed station, in a hospital and to a doctor. After a diagnosis is established it is sent back the same way via satellite. There are now more than 1500 satellites in orbit which can be divided with regard to their altitude and orbits as: far geosynchronous orbit (GEO), medium (MEO), and low (LEO) altitude orbit satellites. Similar to GPS, the Russian space program has launched 24 satellites (GLONASS) with an 11 h 15 min orbital period, which is considered to be far orbit. There is also the Global Navigation Satellite System, and many others. On satellites, there are transponders (passive) or repeaters (active), which send received information back to the earth. Active repeaters have onboard processors connected with other communication electronics. In mobile satellite communication (MSC), measured physiological signals, particularly ECG and blood pressure and also a color image and audio signal obtained from a patient, are mostly transmitted from emergency vehicles (25).
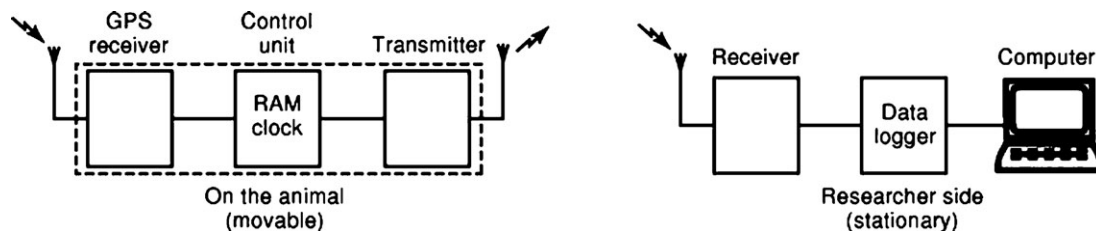


**Figure 18.** GPS tracking.

## BIBLIOGRAPHY

1. Y. Winter, Techniques for the laboratory construction of miniature hybrid-circuits: A 350 mg ECG-transmitter, Proc. 14th ISOB, Biotelemetry XIV, Marburg: 1998, pp. 65–70.

2. R. S. Mackay, *Biomedical Telemetry, Sensing and Transmitting Biological Information from Animals and Man*, 2nd ed., Piscataway, NJ: IEEE Press, 1993.

3. C. A. Caceres (ed.), *Biomedical Telemetry*, New York: Academic Press, 1965.

4. A. Šantić, Theory and application of diffuse infrared biotelemetry, *Crit. Rev. Biomed. Eng.*, **18** (4): 289–309, 1991.

5. V. V. Parin (ed.), *Biomedical Telemetry*, Moskow: Medicina, 1971.

6. A. Šantić, M. Šaban, V. Bilas, A multichannel telemetry system for force measurement in the legs and crutches, Proc. 10th Int. Symp. Biomed. Eng., Zagreb: 1994, pp. 28–33.

7. T. R. Crompton, *Battery Reference Book*, London: Butterworth, 1990.

8. A. Šantić, M. R. Neuman, V. Bilas, Enhancement of infrared biotelemetry for monitoring ambulatory patients over wide areas, Proc. 14th ISOB, Biotelemetry XIV, Marburg: 1998, pp. 91–96.

9. J. W. Hines, *et al.* Advanced biotelemetry systems for space life sciences: pH telemetry, Proc. 13th ISOB, Biotelemetry XIII, Williamsburg, VA: 1995.

10. T. Feuerabendt *et al.*, Radiotelemetry on song-birds, Proc. 14th ISOB, Biotelemetry XIV, Marburg: 1998.

11. B. Woodwared, R. Sh. H. Istepanian, Acoustic biotelemetry of data from divers, Proc. 15th Annu. Int. IEEE Eng. Med. Biol. Soc. Conf., Paris: 1992, pp. 1000–1001.

12. M. R. Neuman, P. T. Schnatz, R. J. Martin, Telemetry of basal temperature in women and respiration in neonatales, Proc. 8th ISOB, Biotelemetry VIII, Dubrovnik: 1984, pp. 137–140.

13. J. G. Webster (ed.), *Medical Instrumentation, Application and Design*, 3rd ed., New York: Wiley, 1998.

14. K. Saito, *et al.* Telemetry capsule for measuring pH of gastric juice, Proc. 12th ISOB, Biotelemetry XII, Ancona: 1992, pp. 415–419.

15. K. Van Schuylenbergh, R. Puers, A computer assisted methodology for inductive link design for implant applications, Proc. 12th ISOB, Biotelemetry XII, Ancona: 1992, pp. 394–400.

16. G. Bergmann, F. Graichen, Telemetry for long term orthopaedic implants, Proc. 9th ISOB, Biotelemetry IX, Dubrovnik: 1987, pp. 295–302.

17. S. Taylor, A telemetry system for measurement of forces in massive orthopaedic implants in vivo, CD-ROM Proc. 18th Annu. Int. IEEE Eng. Med. Biol. Soc. Conf., Amsterdam: 1996.

18. P. M. Meadows, P. Strojnik, Powering Sensors with an Implanted FES System (online). Available http://www.cdd.sc.edu/resweb/resna45.htm

19. G. Schreier, *et al.* A Non-invasive Rejection Monitoring System Based on Remote Analysis of Intramyocardial Electrograms from Heart Transplants, Proc. 17th Annu. Int. IEEE Eng. Med. Biol. Soc. Conf., Montreal: 1995.

20. P. Wouters, M. De Cooman, B. Puers, Injectable biotelemetry transponder for identification and temperature measurement, Proc. 12th ISOB, Biotelemetry XII, Ancona: 1992, pp. 383–391.

21. M. Taillade, Trends in satellite-based animal tracking, Proc. 12th ISOB, Biotelemetry XII, Ancona: 1992, pp. 291–297.

22. M. Soma, A. Nakamura, M. Tsutsumi, The design of satellite-linked transmitter for migratory study of dolphins, Proc. 9th ISOB, Biotelemetry IX, Dubrovnik: 1987, pp. 319–322.

23. J. J. Cupal, L. J. Lacy, F. G. Lindzey, A GPS animal tracking, Proc. 12th ISOB, Biotelemetry XII, Ancona: 1992, pp. 298–304.

24. Anonymous, Leaflets from Trimble Navigation Limited, San Dimas, CA: Sunnyvale, CA, and Magellan Systems Corporation.

25. H. Murakami, *et al.* Telemedicine using mobile satellite communication, *IEEE Trans. Biomed. Eng.*, **41**: 488–496, 1994.

ANTE ŠANTIĆ
University of Zagreb, Zagreb,
Croatia