Chapter 6

Biotelemetry

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INTRODUCTION I

Telemetric transmission of functional and physiological information offers many advantages in medical diagnostics and patient surveillance [1–4]. The telemetric data link avoids direct connections to the recording or monitoring equipment, which are sometimes embarrassing and restraining, thus leaving the patients freely movable. They can be monitored in their natural environment and during work. Accordingly, the measurement does not influence the physiologic system under study, thus avoiding severe artifacts. This advantage is especially important in behavioral studies involving both humans and animals. Implantable telemetry systems transmit internal physiologic signals, or serve to control and program implanted devices, such as stimulators and drug infusion systems, without the need of transcutaneous wire connections which always carry the risk of infection.

II CLASSIFICATION AND PRINCIPLES OF BIOTELEMETRY

Biotelemetry is defined as the transmission of biomedical signals and parameters to a remote recorder by means that do not cause substantial disturbances and restraints to the animal or human being monitored. The classification of systems is based on the technical principle of transmission (i.e., wireless or by wire, radio wave, ultrasonic wave, or light wave). Further classification is according to the range of transmission, number of simultaneous data channels, modulation technique, and application (implanted, ingestible, or portable), as shown in Table I.

Depending on the distance between patient and remote recorder, on-wire transmission is realized either as a direct connection between transducer and recorder or uses interference-reducing preamplifier-driven cable connections, or even interference-proof signal modulation (Fig. 1). Wireless telemetry transmits the signals by modulation of a carrier wave that serves as a transmission link (Fig. 2). Besides the commonly used battery-operated systems, passive telemetry transmitters, which do not require any power supply, exist for applications in long-term implantable devices, offering unlimited operation times.

TABLE I

Application of Various Biotelemetry Techniques and Devices

	Transmission link								
Application	Wire telemetry	Radiotelemetry	Ultrasonic telemetry	Light telemetry	Telephonic telemetry	Implanted devices	Ingestible devices	Portable devices	Fixed devices
Animal application									
Remote measurements		x	x	x		x	x	x	
Tracking		x	x					x	
Human application									
Patient monitoring	x	x	x	x	x	(x)		x	
Function tests		x	x	x	x	x	x	x	
Rehabilitation		x	x	x	x			x	
Remote diagnosis	x				x			x	
Mobile clinical emergency systems		x						(x)	
Work and sport		x	x	x			x	x	
Research		x	x	x		(x)	x	x	

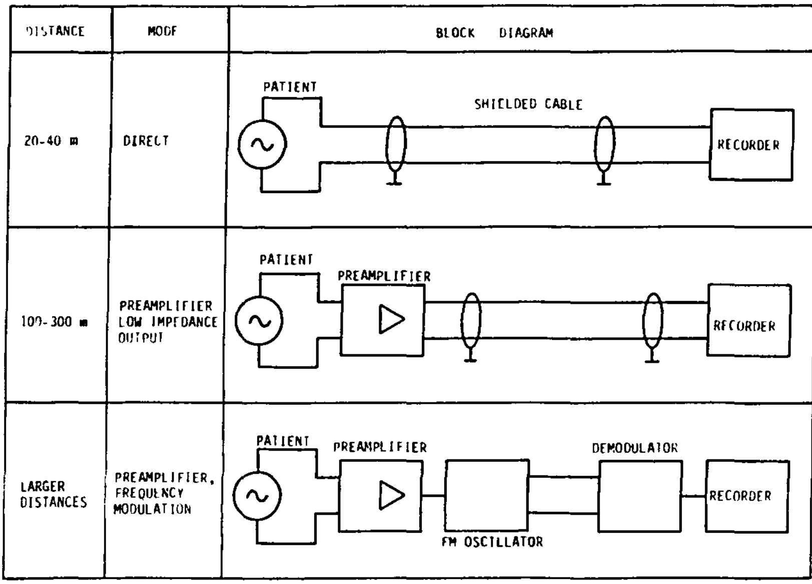

Fig. 1. Block diagrams of wire telemetry for different transmission ranges.

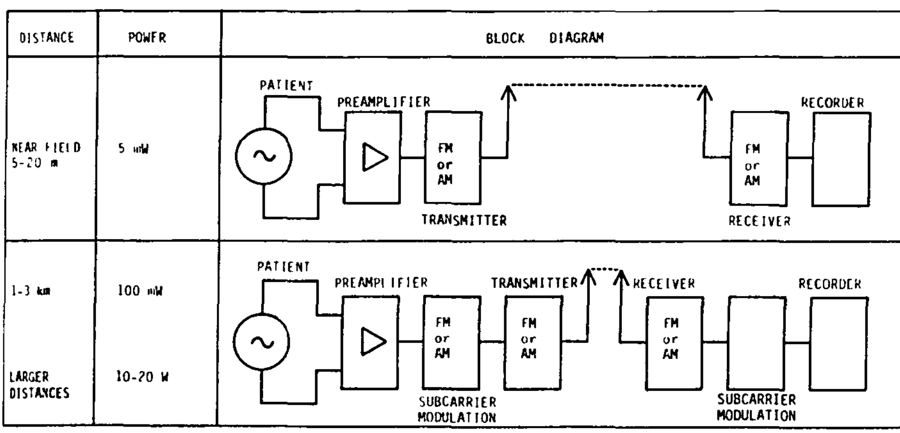

Fig. 2. Block diagrams of wireless telemetry for different transmission ranges.

CABLE TRANSMISSION III

The easiest way to transmit data from the patient to the recorder is to use a shielded cable link. Transmission is limited in range and bandwidth because the cable reactance causes frequency-dependent attenuation of the signal. Within the bandwidth range of physiological signals, cable capacitance is the most important limiting factor. The bandwidth of a shielded cable, driven from a voltage source with an output resistance R, is given by

$$f_{3dB} = \frac{0.16 \times 10^{12}}{RCl} \text{ (Hz)} \tag{1}$$

where C is the capacitance of the shielded cable in picofarads per meter and l the length of the cable in meters. Thus a 300-m shielded cable with a capacitance of 100 pF/m, driven from a source resistance of 100 Ω, provides a bandwidth of 50 kHz. Additional parameters, such as cable inductance and resistance, further reduce bandwidth or transmission range. Thus wire transmission in excess of about 50 m uses signal preamplifiers offering signal gain and an output impedance matched to that of the cable. The cable is terminated with the same impedance. The signal receiver is usually a differential amplifier, avoiding ground loops and suppressing common mode interference signals. Transmission over very long distances, where signal attenuation, noise, and interference are severe problems, is done by using a high-frequency carrier that is modulated by the signal in amplitude or frequency. Thus, by modulation, the attainable signal-to-noise ratio (SNR) for the transmitted signal can be increased substantially.

IV RADIOTELEMETRY

Many different types of radiotelemetry systems are being used [5]. Their basic construction, however, is always the same. Transducers provide the signal to be transmitted, and a radio-frequency (rf) carrier is modulated by the signal and fed to the radiating antenna. For short-range transmission, the antenna is often omitted, radiation being emitted by the oscillator coil as in the simple radio transmitter shown in Fig. 3a. The antimony/silver chloride (Sb/AgCl) electrodes that are in contact with the gastric acid represent a galvanic element that provides pH-dependent voltage modulation of the transistor. The magnesium/antimony (Mg/Sb) electrodes together with the physiologic sodium chloride (NaCl) solution form a battery providing the operating power. The capsule is swallowed and then transmits a frequency according to the sensed pH.

In most applications, however, batteries are required as well as a distinct modulator. Figure 3b shows an ultrahigh-frequency (UHF) tunnel-diode (TD) transmitter. Frequency modulation is achieved by the two variable capacitance diodes (CD) that are controlled by the signal voltage U_s. The

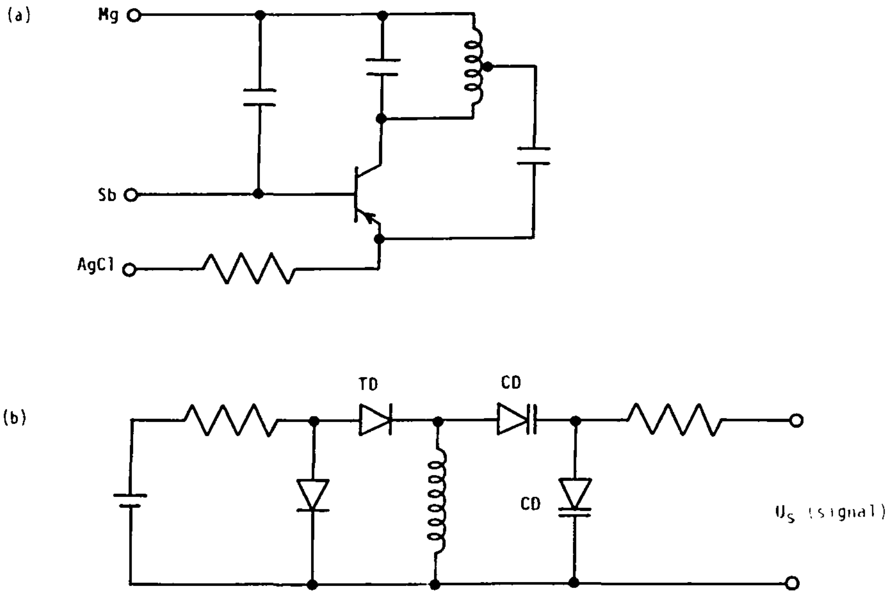

Fig. 3. Circuits of simple radio transmitters. (a) Single-stage electrode powered pH-transmitted and (b) tunnel-diode battery-operated modulation stage.

frequency range of this transmitter is about 100–250 MHz, the mass without battery is less than 0.5 g, the volume is a disk of about 5 mm diameter and 2 mm height, and the range of transmission is up to about 20 m. Longer ranges are achieved by additional rf amplifiers and/or antennas, increasing the emitted power. A two-stage circuit for accomplishing this is shown in Fig. 4.

The need for short-range telemetry with an operating range of only a few feet might seem questionable. However, wireless transmission is required from totally implanted devices to eliminate any transcutaneous wires with their healing and infection problems. Transmission from the implanted system to the body surface is all that is required to solve this problem.

The range of radiotelemetry systems is affected mainly by power, frequency bandwidth, and antenna gain. Environmental conditions, such as shielding by steel–concrete buildings, also influence transmission characteristics. Steel–concrete is penetrated easily only by carrier frequencies above 100 MHz.

Two principles of electromagnetic energy transmission are possible: induction and rf radiation. Inductive coupling is effective only over very short ranges of several feet, whereas rf waves enable far-reaching transmission links. Inductive transmission is based on the electromagnetic coupling

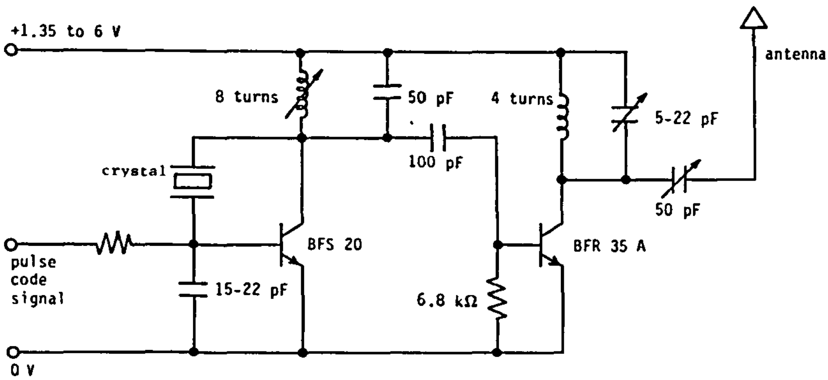

Fig. 4. Circuit diagram of a two-stage transmitter for pulse code telemetry. Frequency range is 100–150 MHz.

of two transmission coils, where the information is transferred from the primary coil to the secondary coil by induction flow. Long-range transmission is based on the emission of radio waves from the transmitter antenna and the sensing of the high-frequency electromagnetic field by the receiving antenna. As induction and radiowave systems base on dissimilar principles of transmission, optimum carrier frequencies differ greatly.

V CARRIER FREQUENCY

Inductive systems typically use frequencies in the range of 1 kHz to 1 MHz, much lower than radio-wave transmitters which have frequencies between 20 and 500 MHz. This has several advantages: simple construction, adequate frequency stability without employing crystal oscillators, negligible generation of rf radiation, and thus, usually, no regulatory control to impose severe restrictions on radiation transmitters. Disadvantages include the fact that the low carrier frequency of inductive systems, which are sometimes subject to invincible limitations (e.g., in metallic encapsulated implants where the frequency cannot surpass 20 kHz for reasons of eddy currents), also limits the maximum possible rate of data flow within the telemetry system.

High transmission frequencies are chosen for radio-wave transmitters for several reasons: Passive components such as capacitors and coils have very small sizes to facilite miniaturization, high data transfer capacity is enabled, the small wavelengths do not need large antennas, and in-house transmission is possible over longer distances in spite of metallic constructions.

MULTIPLEXING VI

Many applications require the transmission of various signals at the same time. For this purpose multichannel telemetry systems provide simultaneous data transfer by either frequency-division or time-division multiplexing procedures. Frequency multiplexing uses subcarriers with various frequencies that are frequency-modulated by the measuring signal. Figure 5 shows a two-channel frequency-division multiplex radiotelemetry system. The subcarriers are linearly mixed, and the resulting signal modulates the main carrier. The subcarrier frequencies must be chosen such that no overlapping of the signal-modulated spectra occurs. The receiver first demodulates the carrier signal and then separates the modulated subcarriers by appropriate bandpass filters. Subsequent subcarrier demodulation yields the single signals.

In a time-division multiplexing system, as shown in Fig. 6, the single channels are sampled periodically. If the sampling theorem is satisfied (i.e., the sampling frequency is at least twice the highest signal frequency), no information is lost. The sampling values of the different channels are then arranged side by side by a commutator that opens the transfer channel successively for the various signal channels, which results in a pulse train representing each of the channels for a certain time interval. In the receiver, another commutator demultiplexes the signal samples, which are

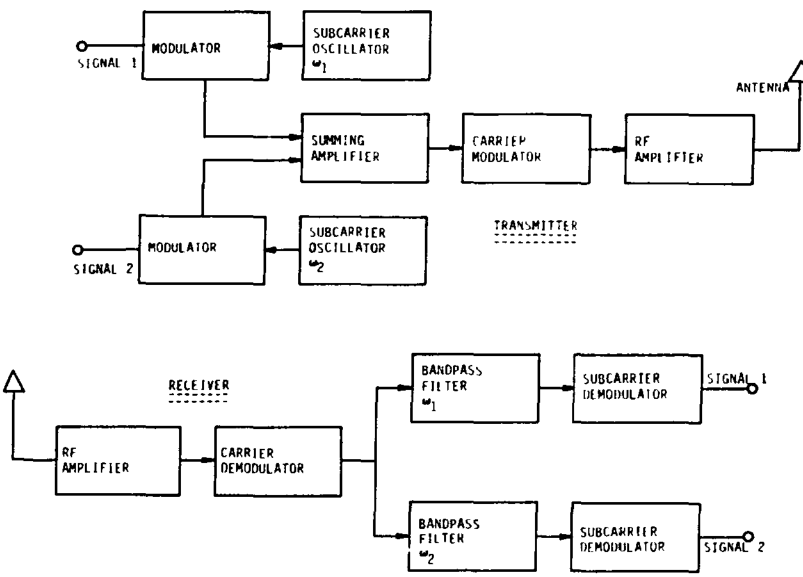

Fig. 5. Block diagram of two-channel frequency-division multiplex radiotelemetry system.

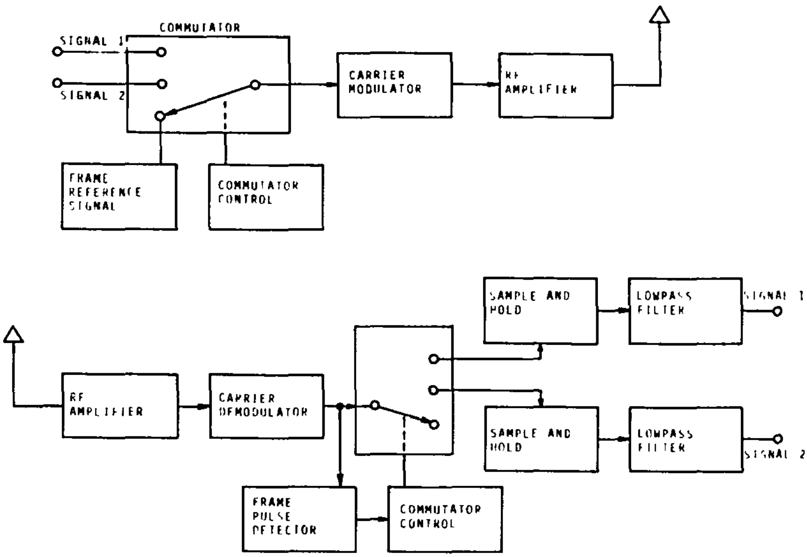

Fig. 6. Block diagram of two-channel time-division multiplexing radiotelemetry system.

first fed to a sample-and-hold circuit and then reconstructed by low-pass filters. To identify the single channels in the receiver, an additional channel, the frame reference signal, is transmitted to indicate the beginning of a new cycle. The reference signal is marked by some characteristic property, for example, a longer duration or a special amplitude. The bandwidth of the signals is determined by the sampling rate.

VII MODULATION

The physiological signal alone cannot be transmitted with reasonable efficiency as a radio wave because of its low frequency. Therefore a high-frequency carrier wave is used as a transmitting vehicle. The signal information is forced upon the carrier by modulation, that is, by a signal-dependent (and thus time-variant) characteristic parameter such as amplitude, frequency, or phase [6].

Amplitude modulation (AM) is a simple method of signal transmission; its application, however, is rather limited. Since the amplitude of the received signal depends on many parameters, such as distance between transmitter and receiver or orientation of the antennas, absolute signal amplitudes can only be determined in the receiver if a calibration signal is included in the transmission. Moreover, AM signals are more adversely affected by sources of interference that additively superimpose the carrier than are the signals modulated by other procedures. Demodulation of an AM signal is simply done by rectifying and lowpass filtering the carrier, which corresponds to envelope detection.

Frequency modulation (FM) provides absolute values for the signal amplitudes. Fading (i.e., amplitude variations in the received FM signal due to time-variant transfer conditions such as changing antenna orientations) is compensated by an automatic gain control (AGC), thus always ensuring the same conditions for the demodulator. Noise interferes much less with the reception than in AM systems, since the addition of a disturbing signal up to a certain limit does not influence demodulation which determines only the momentary frequency of the carrier, independent from amplitude. See Fig. 7.

Many different methods of FM demodulation are known. Direct demodulation converts the FM signal to an AM signal by differentiation. Succeeding envelope detection provides the signal. Indirect demodulation uses a phase-locked loop (PLL) that is especially efficient in the presence of noise.

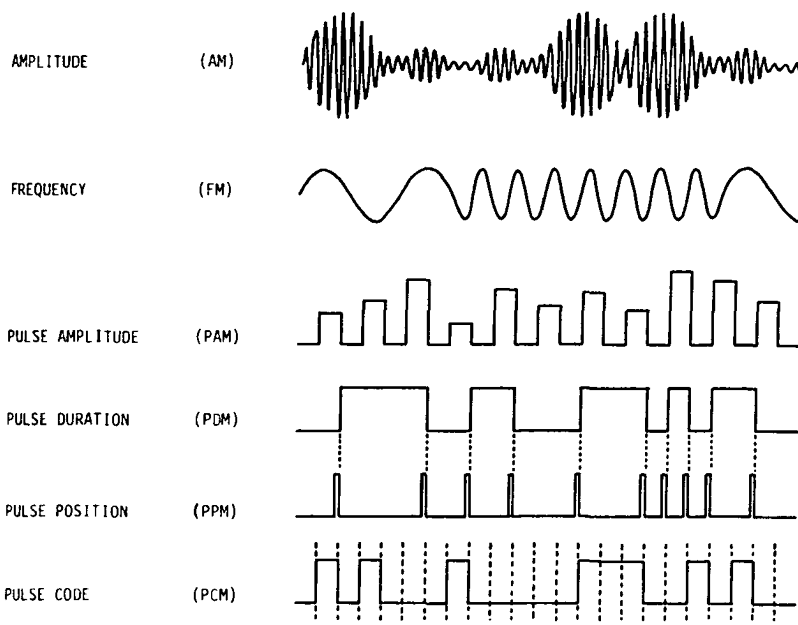

Fig. 7. Modulation and coding techniques.

Multichannel telemetry systems use double modulation. Both the subcarriers and the radio-wave carrier have to be modulated. Modulation principles must not be identical but are chosen according to the best realization for the special application. Four different combinations are possible: AM/AM, AM/FM, FM/AM, and FM/FM.

VIII PULSE MODULATION

In pulse-modulation techniques, only discrete samples representing the signal are used to modulate the carrier. The advantage of signal sampling can already be seen in the realization of the time-division multiplexing telemetry system. In pulse modulation these discrete samples are used to vary a parameter of a pulse waveform. Such parameters are the amplitude (pulse amplitude modulation, PAM), duration (PDM), or position (PPM) of the pulse. Representative waveforms for the different modulation techniques are shown in Fig. 7. Another coding system is pulse code modulation (PCM), in which the analog signal is converted to digital sample points and the series of binary digits is transmitted.

Using the described basic modulation procedures, one can develop arbitrary complex combined coding and modulation techniques. Digital modulation techniques especially offer a variety of possibilities, each optimized for a special purpose, as for optimum speed, information content, or minimum error probability.

IX PASSIVE TELEMETRY SYSTEMS

For control of medical implants and surveillance of patients, continuous data flow of physiological signals and functional parameters is required. Simple inductive telemetry systems are best suited for this application. However, power consumption by telemetry shortens the operating time of the implant substantially, because the battery capacity is very limited, and the necessary radio-wave power is often higher than the power consumption by the intrinsic implant electronics. In this situation one can use a passive telemetry system, which does not need its own power supply, thus avoiding both lifetime reduction and problems resulting from an inductive energy transmission into the implant (i.e., reduced reliability and additional components) [7].

The function of passive telemetry systems is based on the coupling of two components, either by induction or by electromagnetic or ultrasonic wave fields, so that the extracorporeal component, the information receiver, changes a characteristic parameter (e.g., its impedance) according to variations of the second, implanted component's condition. In this situation, the data transmitter operates as a modulated energy receiver. The two components can be two induction coils in which the load impedance of the secondary coil is reflected back to the primary coil, two piezoelectric crystals in which the impedance of an ultrasound-emitting transducer changes according to the load of the implanted receiver, or two antennas, in which the radio-wave emission is influenced by the load of the receiving antenna. No matter what type of transmitters are used, load modulation of the implanted device can be achieved with neglible power consumption if a field-effect transistor is used as a modulation component (Fig. 8). This of course presumes an electric signal to be transmitted. In the case of nonelectric biological signals other possible variable-load components are piezoelectric crystals with pressure- or temperature-dependent capacitance.

Depending on the type of oscillator used in the primary circuit, variations of the load impedance provide either amplitude or frequency modulation of the carrier. The highest efficiency of the telemetry system is obtained when the secondary circuit is tuned to resonance.

The application of passive telemetry in an implantable pacemaker is shown in Fig. 9. The system uses inductive coupling of coils. The implanted coil alternatively serves as a secondary coil for the passive telemetry

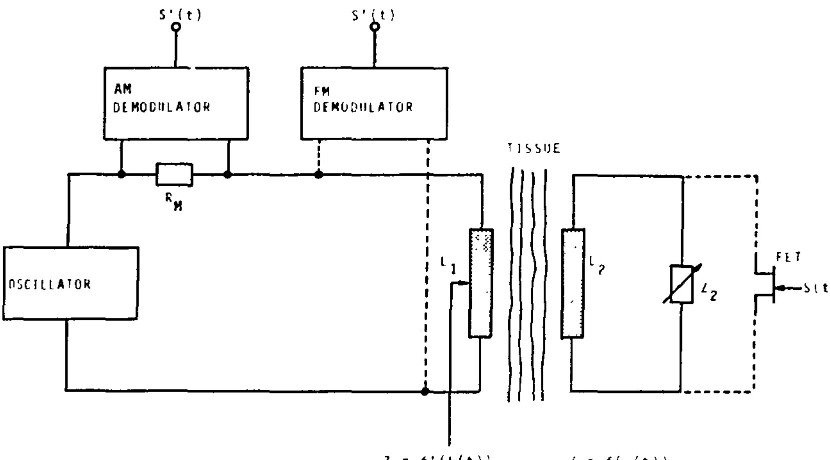

Fig. 8. Block diagram of passive telemetry system.

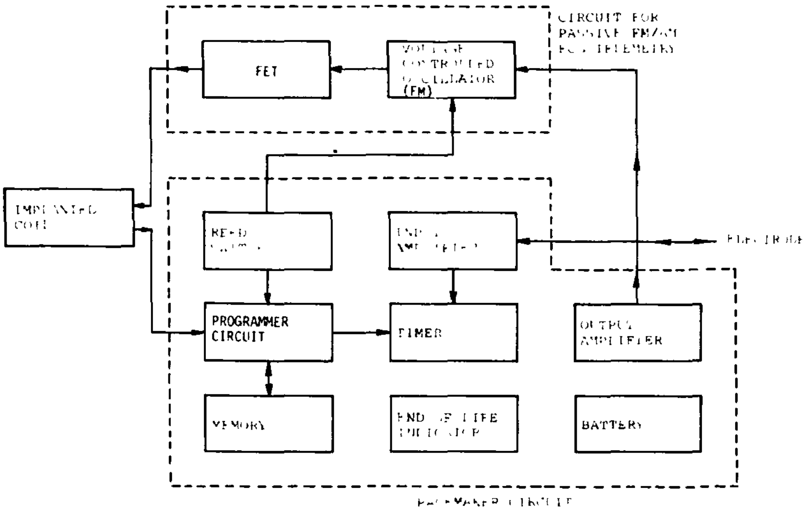

Fig. 9. Block diagram of an implantable cardiac pacemaker using passive telemetry for intracardiac ECG transmission.

system, transmitting the intracardiac ECG as well as pacer parameters to an extracorporeal receiver, or as a secondary coil in a conventional active telemetry system, by which the extracorporeal control system or programmer transmits commands to the implanted device.

X IMPLANTABLE SYSTEMS

Special design requirements apply for total implant systems [8–10]. The most important features of an implant are reliability and long operating life. Both requirements, however, are impeded by further demands, such as low weight, small size, and protection against body fluids by hermetic metallic sealing. Additional problems are tissue incompatibility and the danger of lead breakage. General solutions to these problems do not exist; they depend upon the application. Progress in hybrid and integrated circuit production have partly solved problems of size, weight, reliability, and lifetime. The main limitation, however, remains the power supply, which at present occupies more than 50% of the total space and weight of the implanted system and is responsible for more than 50% of system failures. Chapters 4 and 5 by Tarjan and Gold present a comprehensive treatment of implantable devices.

BATTERIES XI

Various types of power sources have been proposed for telemetry systems, especially implanted systems, where battery exchange always necessitates an operation. They can be categorized as

primary batteries;
secondary, rechargeable batteries;
rf-coupled and magnetic induction power;
body fluid galvanic cells; and
other energy converters.

The most important power sources are the primary batteries, which convert chemical or nuclear energy into electrical energy through irreversible processes. Nuclear batteries (the use of which have been curtailed by possible risks and regulatory procedures) were replaced when technical improvements in chemical batteries provided sufficient power capacities. Besides various types of zinc batteries, the most used primary element is the lithium battery. It offers the combined advantages of high energy density, high open voltage per cell, and long shelf life. Typical values for commonly used batteries are given in Table II.

Rechargeable batteries are sometimes used in telemetry systems with high power consumption [11]. Due to limited reliability and cycle lifetime, however, they are only rarely applied in implantable systems. Rf-coupled and magnetic induction power supplies are also seldom used, since they offer no real advantages over primary batteries. In implanted life-support systems, the risk of failure is too high. In simple measuring implants, primary batteries provide sufficient capacity, or passive telemetry systems can be used; and in extracorporeal telemetry they are not needed anyway. Application of body fluid galvanic cells is limited to the gastrointestinal tract where they are used to monitor the pH, as shown in Fig. 3a. Other

TABLE II

Typical Performance Parameters of Batteries Used in Biotelemetry

Anode	Cathode	Voltage, open	Weight (g)	Volume (cm^3)	Capacity (A · h)	Energy density (W h/kg)	Energy density (W h/cm^3)
Li	LiI	2.8	33	10	3	230	0.8
Li	$LiAlCl_4 + Al_2O_3$	3.66	16	7	2	410	1.0
Zn	NaOH + Ag	1.36	14	3	1	100	0.5
Ni	NiOOH	1.27	12	7	0.2	20	0.05

energy converters have been proposed, such as piezoelectric elements that could provide electric energy by sensing movements such as respiratory rib displacements, but these energy converters are of no practical importance.

XII ULTRASOUND AND LIGHT TELEMETRY

The limitations of radio-wave telemetry–such as legal regulations that prevent the availability of sufficient radio frequencies with adequate bandwidths, interference problems with other radio-wave transmitters, or even physical shortcomings such as the impossibility of radio-wave transmission in underwater telemetry—recommend the use of ultrasound or infrared light as information carriers in some special applications. In underwater animal tracking, ultrasonic telemetry is the most common technique. Infrared light telemetry has proved its value in clinical environments for in-room transmission of data, especially within surgical units, thus avoiding inconvenient cable connections between patient and remote recorders. Technically, there are no major differences from radio-wave telemetry except for the use of different signal transducers.

XIII TELEPHONIC TELEMETRY

Telemetry by public telephone can improve clinical surveillance of nonhospitalized patients. The main application fields are the surveillance of pregnancy, the postoperative monitoring of patients with cardiac diseases, and the control of cardiac pacemakers. See Fig. 10.

Providing the patient with simple measuring equipment enables him either to contact the hospital at regular intervals or to have immediate access to examination if he suspects an emergency. Telemetric monitoring of pregnancy has especially proven its value in rural areas, where the alternatives without telemetry often are hospitalization or the complete absence of surveillance. Besides the psychological aspects of pregnancy that recommend limiting hospitalization to the absolutely necessary minimum and the augmented risk of unmonitored pregnancy, telephone telemetry also offers strong financial arguments.

The basic principle of telephonic telemetry is shown in Fig. 10. The patient system consists of an ECG amplifier, a modulator, usually FM, and an adapter or converter that translates the signal to a form corresponding to the regulations of telephonic data transfer. The receiver demodulates

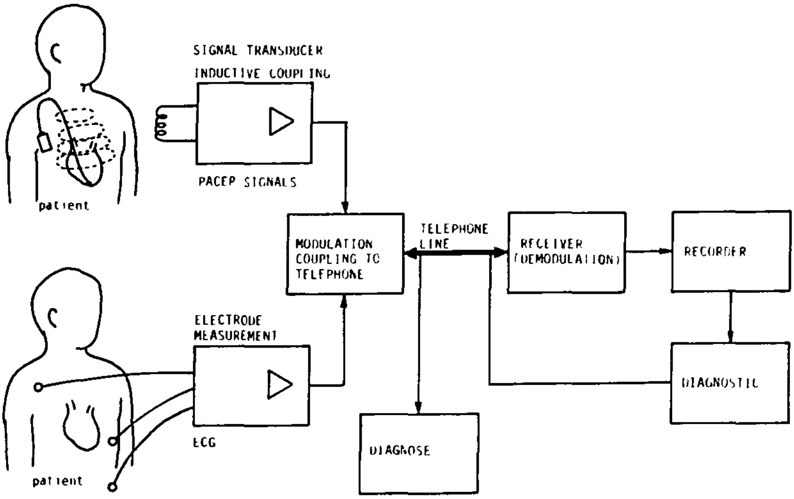

Fig. 10. Block diagram of telephonic telemetry system.

the signal and feeds it to normal registration equipment. Computerized evaluation of the signals provides immediate 24-hr control without any restrictions of patient mobility.

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