BIOMEDICAL TELEMETRY-A REVIEW AND OVERVIEW*

C. A. CACERES, M.D.
Consultant
Washington, D.C.

L. E. SLATER
Technical Representative
Commonwealth of Puerto Rico.

Summary Biomedical telemetry has yet to fulfill the high promise generated by its first significant use ten years ago. Most of the progress has been in research biotelemetry; in the monitoring of animal physiology and behavior to gain new insight into both the normal and pathological state. Many clinical applications have developed but few, with the notable exceptions of telephone telemetry systems in cardiology and the monitoring of astronauts, have achieved wide acceptance. The nub of the problem has been the bias in equipment design and system orientation towards research criteria. There is a compelling need and opportunity for telemetric systems specifically designed for clinical, or on-the-spot, use.

Introduction Biomedical telemetry today stands on the threshold of widespread, valuable use in clinical medicine and health care. Its worth as a technique to gain continuous physiologic data which can be machine analyzed is proven. The quality and unique nature of the information it can produce is universally acknowledged. All signs are "go" for the harvest of this new technology.

Still, despite this progress and acknowledgement, biomedical telemetry seems to be held back by some elusive barrier; a constraining force which keeps it from the great field of clinical applications.

How far has biomedical telemetry really come? What are the problems that still inhibit it as a proven clinical technique? Where is the technique going? These are the questions we will try to answer in this brief review paper.

Let us start by considering the basic contribution that biomedical technology offers: Its

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* The deadline for submitting this paper prevented inclusion of results of a national survey to determine recent progress in biomedical telemetry. This material will be presented at the Conference and available in printed form afterwards from the authors.

ability to organize a research or clinical problem so that it is amenable to the "systems" approach. All "systems" comprise an input, a medium to be traversed, and an output. In medicine and biology, telemetry can be the integrating force which defines the problem as a system. This is the crux of its contribution. Without this integrating force, many medical instruments today fail to achieve their true value--they fail to create a system and simply remain components from which full advantage is not gained.

While the role of biomedical telemetry is to organize information into a systems approach, the goal of the technique is more specific: namely to faithfully convey phenomena so that they are useable units of information. These information units can tie into the normal thinking process of a human being or the physiological mechanisms of the subject. They can similarly tie into a machine interface (for subsequent analysis by the human being), or for action by the machine serving as a control system. Hence the goal of biomedical telemetry--to gain useable information--is what makes possible its role--the role of facilitating the systems approach.

Progress in Technique Considerable progress has taken place over the past ten years in refining and improving the technical aspects of biomedical telemetry. A brief review of this progress will help clarify the difficulties which seem to curb its wider clinical application.

First let us consider the media being used. In the narrower technical sense, biomedical telemetry today usually refers to special informational conversion or transmission generally by radio or telephone. But this does not exclude combinations of the two or lasers, ultra-sound, infrared, and other media which are not yet generally available to all of us.

Whatever the mode of transmission chosen, coding of the data should be devised to save space in the media, to convey not only signal but related information, and to allow for feedback. The media should optimally be adaptive depending on the needs of the signal at specific times.

A practical telemetric system design must include or interface with filtering for noise or preemphasis of the signal, validity checks, buffering, longer-term storage, data reduction, feedback, control circuits, and displays.

For good information transmission we have come to learn that different personnel are required to assume responsibility for three specific areas in telemetry:

First there is the information source, including the transducer as well as the clinical systems involved. Their characteristics and variability must be established as firmly as is possible. The transducer's message results from interaction between the time-varying characteristics of a living source and its relatively invariant (or unadjusting) circuits and components. It has been found necessary for both the engineer and biologist to comprehend the transducer and information source equally well. This does not mean that they each must specifically know the background rationale of why the characteristics exist in transducer or biologic source. But, rather, that they must act as a team.

The second area of concern involves the amplification factor, noise, and the transmitter which codes the message or signal. The methodology for this is within the realm of today's standard electrical engineering practice, and these items are open to creativity on the part of the engineer. The biologist need not be more than passively knowledgeable about this technique if he has conveyed to the engineer the true sense of what the biologic system can be expected to do.

The third area includes the receiver and the subsystem responsible for decoding and final transmission of the information to its user. Technical details here are primarily the concern of the engineer.

Evaluation of final information the system produces is a matter for both biologist and engineer. The display can mislead if how it is produced is not comprehended. The final checkout requires that the interpretation makes sense, not just to the biologist but to the engineer as well.

Noise and Distortion Superimposed on the telemetry system is a noise source which has come to be considered an undesirable but always present element. Individual component noise factors are significant, but in providing the user with performance specifications only the total value is of importance. The more components, the more interfaces, the longer the transmission distances--all of these tend to increase noise. Higher-quality equipment may decrease it, but cost then enters the noise picture and tradeoffs are necessary. Numerous noise reducing methods can be considered by the engineer, but it is clear today that a good telemetric system need not be completely noiseless. Optimization is what we are after for useable information units.

Practical applications of biomedical telemetry have proven we can cope with noise of certain values, and we may even wish to have certain distortions to aid us in our analysis. For example, high frequency-response loss in equipment results in slurring of the signal which rounds off corners or peaks. Amplitudes are diminished and minute waves disappear. But, this distortion may be useful in evaluating the electrocardiographic signal from a subject with extraneous low-level random noise. Low frequency distortion is helpful, as another example, in fetal electrocardiography. Maternal abdominal motion and respiration can be eliminated for a better fetal electrocardiogram by elimination of low frequencies, i.e. distortion. A goal of a good telemetric system is thus transmission of known or established quality and characteristics.

Data Characteristics The combined effect of resistance, capacitance, and inductance depends on their individual values in the system as well as on the nature of the input signal. The engineer can calculate this. He has learned he should contrast hardness of that type of data with medical, empiric soft data.

Biologic and medical signals have characteristics which are often due to historical as well as physical or even physiological considerations. Biology was early studied with devices with poor high-frequency response. String galvanometers and the like generally had good low frequency response. Body signals, however, have been studied with these for decades, and relationships between instruments and body characteristics were established by trial and error. In the past we established dogma based on knowledge of the basic signal, or the data acquisition system. In effect, in the past 100 years we developed a cryptographic method of analysis of data generally recorded with instrumentation of reasonable low-frequency response and without complete analysis of input characteristics. Nevertheless clinicians have used the data and achieved reasonable results.

Miniaturization Sensors or transducers should not change what the subject would ordinarily engage in nor should they encumber an ill patient. Hence, miniature radio transmitters attached to the sensor or transducer have been found to be a good way to reasonably collect medical and biological data outside of a strict laboratory environment.

Miniaturized instrumentation for transducers and sensors was given a healthy stimulus by the astronaut program. Endoradiosonds in biological experiments relating to animal behavior, or for intracavitary organ data, for example, can transmit values of pressure, temperature, acidity, oxygen tension, blood pressure, radiation intensity, motion, bleeding sites, and other vital information such as the electrocardiogram and the electroencephalogram. Too few researchers and clinicians have made use of these. In part this has been because of cost.

With miniaturization, telemetry has been used not only to obtain data, but to provide a signal stimulus. This and the feedback are significant contributions in the field of research. Telemetric systems can of course trigger electrical, thermal, or any other type of stimuli. The results suggest future methods for the study of human responses. Now that the physiologist is able to transmit the stimulus and observe results in one’s own environment, several types of studies are possible.

Today there are active and passive transmitters. The passive transmitter requires no battery within its capsule and obtains its energy from external sources. The capability of small transmitters as devices that trigger servo-mechanisms within the body must be mentioned as a future possibility.

Telephone Transmission The most widely used medical telemetry system is the telephone. Telephone transmission of medical signals has three principal justifications.

The first of these is the convenience due to its ubiquity. Telephone transmission systems are able to eliminate certain problems involving identification of the patient, intermediate storage, transportation to the central site. This may all sound too simple. But, by sending a signal to its ultimate destination at the time it is acquired from the patient, and thus eliminating intermediate manipulation, the path to on-line processing of all data becomes cleared for mass use.

A second justification has been found to be time saving. When the distances involved are long, telephone transmission can allow data to be sent and returned while it is still usable. In an emergency situation, this advantage of telephone telemetry is obvious. This particular value was one of the first to be widely recognized as consulting cardiologists had telephone data receivers installed in their home and office. These allowed them to give informed consultations immediately, without risk of life-threatening delay.

The third justification of telephone telemetry, one that is not immediately apparent, is its "translation ability". In order to receive signals or data from any patient location or laboratory, a center need have only a telephone receiver. Whether the data is recorded on various types and brands of tape recorders, or in different format, or with different electrical specifications, it will enter the center via the telephone in a universal form and be immediately adaptable to the center's own equipment. The telephone supplies a matching interface for transmission of data from machine to machine, regardless of individual characteristics.

The first transmission of medical data by hardwire and components of a telephone system was in 1903 by Einthoven who recorded electrocardiograms from a hospital and transmitted them to his laboratory where his string galvanometer amplified the signal.

These pioneer efforts did not stimulate much other than the inclusion of hardwire in a few hospitals for transmission of electrocardiograms from wards to the electrocardiographic heart station. Part of the problem, of course, was the lack of appropriate amplification and filtering, etc., that is lack of electronic telemetric systems.

Many of the problems were solved with the availability of FM systems and thier decreased sensitivity to variations in signal amplitude as opposed to amplitude modulation. This and the fact that the systems require less gain in the amplifiers and are inherently less noisy than amplitude modulation led to the now almost universally accepted usage of FM in medical telemetric systems.

The first commercially available medical telephone package appeared in 1958 designed for electrocardiographic transmission. Although somewhat difficult to operate it was used with some acceptance in the Kansas City area to allow practitioners to send electrocardiograms from their offices to that of cardiologists for interpretation of the signals.

Transmission of data by telephone is fairly well stabilized today. Three channel multiplexing of medical signals is a routine in many cases. At the present time, we are generally capable of reasonable quality transmission with existing telephone systems in the United States and, to a large extent, elsewhere. The telephone companies maintain certain tariffs for their data sets. Medical-data transmission from others' data sets also fit readily into their standard data systems.

Regretfully there is still lacking sufficient interplay between the telephone companies and the manufacturer of the transducers and interface devices that can be used to send data through the telephone. Often custom connections must be made. It would be desirable to have standardization of output from every medical transducer in order to have direct input into a telephone either by direct connection or audio transmission. Higher quality would result. This area should be investigated by the manufacturers and the telephone companies for their and, particularly, the users benefit. Medical instrumentation groups should also look into this area of public interest.

Another area for suitable cooperation would be in the development of coding systems to allow the user to transmit identifying subject codes and other ancillary data in a format suitable for the telephone as well as the transducer. Identification mechanisms are an indispensable item that has been left off most medical instrumentation in the past producing huge record-room problems. Too much effort is now being put into solving the record room problem without looking into the initial cause of the problem. These initial coding problems are easily solvable by automation systems, if the coded information is carried along with or preceding the signal. This is a job for the telemetric system. The idea of voice communication for coding on the same channel is inadequate.

Radio Transmission The first radio transmission occurred in 1921 when the U.S. Army SignaTCorp used a radio telemetry system for heart sounds. It was intended that these be recorded on ships without physicians on board so that facilities on shore could do the actual analysis.

With radio as regulated by the Federal Communications Commission, it should be noted that a system that interferes with other radio operations can be considered illegally operated, regardless of conformity to general specifications. The first medical radio license was granted for medical signal transmission from ambulances. The definite or special (if there be any) requirements for medical or biological radio transmission, either short or long range, have not been established. In part this is due to lack of users and expertise. Thus, rules and regulations standardizing equipment and modes of transmission may yet be premature, other than as generally stated by the FCC for other similar users.

A Model for Medical Telemetry Perhaps the most remarkable and finest model of biomedical telemetry exists in the astronaut monitoring programs. Yet it is the sad truth, both in reviewing telephone and radio, that we are years behind in adapting this to medicine, as contrasted to space technology contributions to other fields. The astronaut programs combine various methods of telemetric communication and a multitude of advances in the field of electronic technology. The worldwide network of tracking stations both on land and on ships allows inflight information to be transmitted and received for immediate analysis.

Astronaut monitoring has allowed display on earth of a multiplicity of biological signals. Temperature, electrocardiogram, respiratory curve, and blood pressure are of course the most significant for vital sign determination. Electroencephalograms and electromyograms are other suitable signals.

In general the number and type of signals required for space monitoring are no different than the class of signal required by the anesthetist in the operating room, the physician in his intensive care suite, or the biologist in the research laboratory. We must match the advances made by the astronaut program with the advances made in the medical world in interpretation of the signals by computers and have a real-time on-line aid to the medical monitor.

There is also no difference in the volume and presentation of data required by the clinician or the space-flight monitor. Trend information has been shown to be more reliable than single values. This fact is known in medical practice but is not used as extensively as it should be. Trend data today are usually obtainable after the fact.

However, large masses of data can have immediate analysis by statistical techniques. Computers can handle the data and provide indices of where a subject is in reference to previous training experience or where the subject is in terms of others of similar characteristics or disease.

Clinical Applications Requirements placed on clinical systems of biomedical technology are that components must have reasonable sensitivity, stability, and reliable performance as required for the specific clinical work.

A typical application is to detect the energy from the fetal heart. The utility of radio telemetry in this situation is evident. To initially detect the signal, wires need not be strung on the mother’s abdomen. Wires add artifacts due to movement and induction from AC power lines. Additionally, the subject is more comfortable without them.

Urbach developed a practical system for delivery suites which allows one to monitor the birth process of several subjects. He first recorded from the abdomen of the pregnant female. After the fetal membranes rupture, he attached electrodes to the scalp of the child during birth. To these electrodes are attached miniature transmitters. Neither the birth process nor the mother is disturbed and constant monitoring is possible. The delivery suite can be wired for antennae placed in all required locations in several rooms and hallways at different positions so as not to miss any of the signals. Once received at the antenna the signals are transmitted to a central control room. The whole procedure does not contaminate the area or obstruct it with wires but does afford proper observation. Transmission is necessary for only 50-100 feet. This might well be the practical requirement in most hospital situations that can be envisioned.

Perhaps the greatest potential in the near future for radio telemetry in a hospital situation will be in intensive care suites required to monitor patients with heart attacks or postsurgical suites or the operating room itself. In the distant future the principles learned from these can be incorporated into monitors for every patient in the hospital. This would diminish the requirements for increasing nursing personnel and could diminish their constant performance of basic necessary but routine monitoring activities that do not require the skill that the nurse possesses. Hospital design will be markedly changed as a result of these advances.

Pioneering systems of biomedical telemetry have been described for neurosurgical procedures, anesthetic, surgical, and other specialized needs. The primary problem is determination of what parameters are actually needed, how much data is required from these parameters and data presentation modes in each specific circumstance.

Telemetric monitoring offers an advantage noted particularly in coronary care units. Hazardous conditions, such as ventricular tachycardia,detected early, can in most instances be successfully treated without fatality. Monitoring systems to sound an alarm, offer remote control, and initiate therapeutic measures require the use of on-line computers to analyze and interpret the data. Telephone telemetry of the initially radio received signal incorporated into a computer system (i.e., integration of various subsystems) offers an important key to practical widespread application of clinical telemetry.

On-line, real-time computer monitoring of any medical signal is now possible. For example, pacemaker performance can be monitored and checked by telephone. The computer’s analysis can include English interpretations for any required time period. It can include a comparison with any other required time period, and can also have predictive statistical interpretations attached to it. Further means to trigger alarm displays can be provided by real-time on-line computer monitoring.

Need for Clinical Design Foremost in designing a biomedical telemetry system should be whether the data will be for clinical purposes of on-the-spot action, or for further research. Research and clinical systems are vastly different and should always be considered so. There have been far too many systems oriented toward the researcher and sold to the clinician. There is a vast need for clinical and nursing telemetering aids, specifically designed to meet clinical requirements.

If service systems include recording for storage, they can facilitate research as the result of clinical experience. This mode of research has been stressed too little in the past and may, in fact, be the most important of all. The laboratory of the future may be the clinical ward rather than the isolated and too unrealistic laboratory.

ON THE TIMING PROBLEM IN OPTICAL PPM COMMUNICATIONS*

R. M. GAGLIARDI
Department of Electrical Engineering
University of Southern California.

Summary The use of digital transmission with narrow light pulses appears attractive for data communications, but carries with it a stringent requirement on system bit timing. In this paper we investigate the effects of imperfect timing in a direct detection (non-coherent) optical system using PPM bits. Particular emphasis is placed on specification of timing accuracy, and an examination of system degradation when this accuracy is not attained. Bit error probabilities are shown as a function of timing errors, from which average error probabilities can be computed for specific synchronization methods. Of significant importance is the presence of a residual, or irreducible error probability, due entirely to the timing system, that cannot be overcome by the data channel.

Introduction The ability to generate extremely narrow, high energy light pulses from a laser source has made the optical transmission of digital data extremely attractive for modern communications. This possibility has fostered an exhaustive exploration of optical communication systems, from both a theoretical and hardware point of view (e.g. see [1]). The use of digital transmission with narrow pulses, however, carries with it an extremely stringent requirement on system bit timing- i.e., time control of the system sampling and integration intervals during each data bit. For the most part past analytical studies have assumed perfect system timing, and the degradation caused by timing errors in optical systems have been virtually ignored. In this paper, we investigate the effects of imperfect timing in a direct-detection (non-coherent) optical communication system, with particular emphasis on the specification of timing accuracy, and an examination of the system degradation when this accuracy is not attained.

Consider an optical digital system that operates by transmitting a burst of energy in one of two T sec adjacent time intervals to represent a binary bit. The above represents a two level pulse position modulated (PPM) mode of transmission and is known to be optimal under various criterion, when constrained in average transmitter power [2]. We shall assume the transmitter and receiver operate diffraction-limited, so that the transmitted energy corresponds to optical energy in a single spatial mode of the optical beam. Note that T is the energy pulse width in time, 2T is the bit interval, and information is being

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