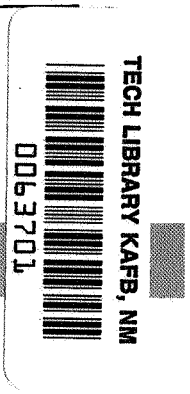

TECHNOLOGY UTILIZATION

NASA CONTRIBUTIONS TO BIOINSTRUMENTATION SYSTEMS

A SURVEY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Contents

CHAPTER 1

Introduction

This survey describes advances in bioinstrumentation devices and techniques achieved by the National Aeronautics and Space Administration (NASA). Its major aim is to facilitate use of NASA contributions in medicine and the bioinstrumentation industry. Accordingly, the survey is directed largely toward two groups: those in medicine who plan, specify, and utilize advanced bioinstrumentation systems; and those in engineering who design, develop, and manufacture them. Together, these groups greatly influence the course of medical practice and public health.

In the last decade, almost coincident with the growth of the space program, there has emerged a challenging problem in medicine. The problem is dual in nature. First, there is an insufficient number of physicians, nurses, and paramedical personnel available to handle the number of people requiring medical care. Secondly, the cost of medical care has become a significant percentage of the gross national product. Solutions to these two problems go hand in hand. The productivity of medical personnel must be such that the available supply of these skills may be stretched to cover an ever increasing patient load; increased productivity will also produce cost savings to the ultimate consumer, the patient.

A good part of the answer to this problem of productivity lies with bioinstrumentation and its more effective use in all phases of medicine. This solution is illustrated by the system for mass screening and diagnosis established for subscribers to the Kaiser Foundation Health Plan in the San Francisco area (refs. 1 and 2). The Kaiser "Multiphasic Health Checkup" provides an instantaneous computer summary of more than 40 medical measurements obtained during a 2½-hour examination, for 25 000 patients annually, at a cost of about $35 per patient, with complete patient acceptance. The system depends heavily on sophisticated bioinstrumentation operated by aides, and on advanced computer methods. Other examples can be found in modern hospitals, intensive care units, surgical suites, medical data handling, and many other situations. But in the main, the tremendous potential of current biomedical instrumentation has not been fully tapped. This is why NASA's experiences in bioinstrumentation planning, development, and application can be valuable to the medical community today.

Bioinstrumentation has been the fundamental tool used by NASA to learn about the medical problems of spaceflight. Bioinstrumentation systems have been integrally connected with the Mercury, Gemini, and Apollo programs. Other systems have been applied to the biological research and simulation studies that support spaceflight activity. The conditions of spaceflight impose uniquely stringent requirements on NASA bioinstrumentation, so that system development requires close cooperation between medical and engineering personnel. Many advances in bioinstrumentation technology have resulted.

In its work, NASA makes two main types of technological contributions. One is in the

production of specific instruments and systems, usually for spaceflight. The other is in the formulation of systems requirements and specifications, and methods for systems development and application. Both types of contribution are significant. In fact, because of the specialized nature of spaceflight equipment, the second may frequently outweigh the first. Accordingly, this survey has been organized into chapters dealing with basic problem areas in bioinstrumentation system development. The objectives are to stress the correspondence between spaceflight and nonaerospace applications and to lay the groundwork for subsequent extrapolation of NASA's experiences by the reader. Within the selected areas, representative examples illustrate NASA solutions to system design problems. The examples chosen emphasize human monitoring during aerospace flight, but contributions to research methodology have also been included.

Choice and classification of examples were often difficult. System developments may fit into several categories; they may differ only slightly from one another; they may be insufficiently documented; or their documentation may be inaccessible. The authors have based their selection on: (1) relevancy to the main point of the chapter; (2) estimated importance of the contribution; (3) completeness of available information; and (4), to some extent, a lack of previous Technology Utilization publication. Information on contributions was derived from the literature, from inquiries, and from personal visits by the authors to the NASA centers and industrial contractors involved in their development.

This survey is not a compendium; it does not contain all NASA developments nor even all significant developments in a particular area. Nor does it trace in detail the history of each development. In a program like NASA's, system needs may be stated at one organizational level, and be filled at quite another level by contract and subcontract, funded research, or some combination of NASA and outside effort. This makes the assignment of individual credit difficult and frequently controversial. For the purposes of this survey, a NASA contribution is defined as one supported by NASA, and only abbreviated indications of industrial, institutional, or individual responsibilities in its development are provided. Generally, the associated references contain more complete information of this type.

Five main areas of NASA bioinstrumentation system development are identified in this survey. They are:

(1) *Planning*—Chapter 2 outlines the techniques NASA has used to establish information requirements and equipment specification for bioinstrumentation system development.

(2) *Sensing and signal conditioning*—Chapters 3 and 4 deal with the detection of physiological signals under aerospace conditions and with the design of advanced electronic instrumentation to process and transmit these signals.

(3) *Medical monitoring and data processing*—Chapters 5 and 6 describe significant NASA contributions to data processing, including acquisition techniques, computation of derived parameters, and methods of data display.

(4) *Measurements in the field*—Many of NASA's contributions represent solutions to the difficult problems of making laboratory-quality measurements in the field. Chapter 7 focuses on this aspect of system development.

(5) *Manufacture*—Chapter 8 presents some NASA contributions to bioinstrumentation fabrication and quality assurance.

Most chapters end with an application evaluation of the technology described. Here, specific nonaerospace applications are discussed, along with possible alterations required to make space technology economically feasible for everyday use. In conclusion, chapter 9 discusses some general factors influencing application of NASA bioinstrumentation developments and techniques to nonaerospace medicine and industry.

The survey covers a broad spectrum of developments. It need not be read in sequence, and the reader with specific bioinstrumentation interests may sample freely from chapter and section.

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CHAPTER 2

Bioinstrumentation System Requirements

This chapter presents NASA's methodology in establishing information requirements and equipment specifications for the bioinstrumentation systems used on suborbital and orbital spaceflights (tables 1 & 2). The questions and decisions underlying the planning approach are discussed, along with the organizational framework used to ensure coordination and timely delivery of required equipment. The NASA program offers valuable guidelines to the planner of bioinstrumentation systems for hospitals, field monitoring, clinical and

TABLE 1.—*Project Mercury Manned Flights*

Flight	Crew	Launch date	Description	Duration (hr : min)
MR–3	Shepard	May 5, 1961	Suborbital	0 :15
MR–4	Grissom	July 21, 1961	Suborbital	0 :15
MA–6	Glenn	Feb. 20, 1962	Orbital	4 :56
MA–7	Carpenter	May 24, 1962	Orbital	4 :56
MA–8	Schirra	Oct. 3, 1962	Orbital	9 :14
MA–9	Cooper	May 15, 1963	Orbital	34 :20

TABLE 2.—*Gemini Manned Spaceflights*

Gemini Mission	Crew	Launch Date	Description	Duration, day :hr :min
III	Grissom Young	Mar. 23, 1965	Third revolution manned test	0.04 :52
IV	McDivitt White	June 3, 1965	First extended duration and extravehicular activity	4 :00 :56
V	Cooper Conrad	Aug. 21, 1965	First medium-duration flight	7 :22 :56
VII	Borman Lovell	Dec. 4, 1965	First long-duration flight	13 :18 :35
VI–A	Schirra Stafford	Dec. 15, 1965	First rendezvous flight	1 :01 :53

TABLE 2.—*Gemini Manned Spaceflights*—Continued

Gemini Mission	Crew	Launch Date	Description	Duration, day :hr :min
VIII	Armstrong Scott	Mar. 16, 1966	First rendezvous and docking flight	0 :10 :41
IX–A	Stafford Cernan	June 3, 1966	Second rendezvous and docking; first extended extravehicular activity	3 :01 :04
X	Young Collins	July 18, 1966	Third rendezvous and docking; two extravehicular activity periods; first docked target vehicle-propelled high-apogee maneuver	2 :22 :46
XI	Conrad Gordon	Sept. 12, 1966	First rendezvous and docking initial orbit; two extravehicular activity periods; second docked target vehicle-propelled high-apogee maneuver; tether exercise	2 :23 :17
XII	Lovell Aldrin	Nov. 11, 1966	Rendezvous and docking; umbilical and two standup extravehicular activity periods; tether exercise	3 :22 :37

physiological research, and similar nonspace situations because of its scope, its focus on critical medical problems, and its use of specially developed, advanced technology.

Space exploration involves a radical departure from the normal environmental conditions of human activity, and the physiological well being of the astronaut has been a prime focus of the entire space program. Medical inputs were required early in the Mercury project to establish basic system requirements—the medical information needed and the best means to obtain it. Medical personnel have continued to play a central role in spaceflight planning.

Each manned spaceflight has been both a unique operational mission and another step in a continuing research program. Medical monitoring must determine the immediate safety of the astronaut and the effect of observed responses on the conduct of subsequent flights. Only a limited amount of bioinstrumentation can be taken into space on each mission, so a careful selection must be made of physiological variables and measurement means. Finally, space bioinstrumentation is highly specialized in design and fabrication. Its development must be begun well before a particular mission and controlled closely up to the time it is used. Because of these factors, and the innate technical complexity of space operations, NASA's work represents a major advance in bioinstrumentation system planning.

BACKGROUND

Since World War II, scientists have speculated on the biological implications of spaceflight. During the 1950s experimental studies tried to answer some of the fundamental questions raised. These studies concerned man's reactions to weightlessness, lift-off and reentry acceleration, space radiation, noise and vibration, and also dealt with the logistics of life support, nutrition, and sanitation (ref. 1). By mid-1958, some information was available from human and animal flights lasting between 30 seconds and several minutes. These data showed no apparent physiological harm for these short flight durations (ref. 2). Concerning more practical flight times, theoretical speculations ran the gamut from predictions of severe debilitation and disorientation to predictions of no effects at all. It was generally recognized, however, that in light of the potential dangers to the astronauts, the medical community would have to contribute substantially to the national space program if its goals were to be met.

Participation of medicine in manned spaceflight technology did not start with passage of the National Aeronautics and Space Act in 1958. More than 30 years of aviation medicine preceded the decisions made then. During those years the flight surgeon had often functioned in the capacity of a medical officer concerned with normal subjects exposed to an "abnormal" environment. It was natural, then, for the aviation medical community to consider space medicine as a new dimension to its existing specialty (ref. 1). Nevertheless, despite some previous experience and the steady growth of animal experimentation (refs. 3 and 4), few hard facts were available to NASA scientists as the nation's manned space program began.

PLANNING FOR THE MERCURY PROGRAM

In October 1959, a special Committee on Life Sciences was formed as a part of the Space Task Group at Langley Research Center, Hampton, Va. (ref. 5). This committee was faced with the job of determining the medical monitoring requirements for the Mercury flights. Reviewing previous work and extrapolating available data, the committee found no conclusive evidence that man could survive prolonged spaceflight exposure. They felt that monitoring of some critical physiological variables was mandatory, but that the variables themselves must be chosen by an engineering-type tradeoff analysis comparing significance and implementation possibilities. A biotelemetry system was planned for the Mercury capsule. But in light of the flight schedule—an orbital flight in 1960—development time was short. In addition, the whole concept of continuous monitoring of physiological data via telemetry from an active pilot was somewhat novel in 1959. Without exaggeration, one could say that no equipment existed in a form suitable for continuous and reliable monitoring in space and that few physicians had had experience with analogous equipment on Earth.

Thus the two major questions influencing the NASA choice of physiological variables for monitoring were: Could man survive space exposure? And what instrumentation could be developed in the time available to measure variables related to survival and also meet operational requirements of comfort, reliability, compatibility with other spacecraft systems, and noninterference with the pilot's primary mission (ref. 6)?

A requirement was established early for continuous recording of the selected variables, which would be made available immediately after telemetry acquisition to the ground-based medical monitoring team. Continuous records were felt necessary to determine the astronaut's capability of completing a mission and to provide clues in the event of precipitous collapse. Since survival was the main goal, the monitoring philosophy became known as "safety monitoring."

Medical interest centered on the cardiovascular system because hydrostatic changes were the most obvious concomitant of the weightless state (ref. 6). Instrumentation considerations consequently focused on the acquisition of cardiovascular information. At the same time, it was recognized that abnormal indications from the cardiovascular system could not be explained in terms of weightlessness unless other environmental parameters were also measured. However, the only cardiovascular instrumentation that could be developed and qualified in time for the first flights was for measurement of heart action potentials—the electrocardiogram (ECG). Thus this measurement became the mainstay of the safety monitoring system although others were later added. Two pairs of electrodes, yielding two ECG leads, were specified to increase reliability. Unfortunately, these leads were in nonstandard body locations in order to reduce body movement interference. Classical waveform diagnosis was thus sacrificed in favor of good information on cardiac rate and rhythm.

Both central venous blood pressures and arterial pressure were considered invaluable. But there was no known way to measure the former consistent with prudent medical practice and spacecraft operational requirements. And while continuous arterial pressure was of

great interest, particularly during reentry following weightless exposure, direct measurement was out of the question.* Work had been done on automatic indirect sphygmomanometers, but no system had been developed to the point where it could be qualified for the first manned flight (ref. 8). Accordingly, blood pressure measurement was not included at the start of the space program, but a semiautomatic apparatus was ready and used on the MA–6 Mercury flight.

Body temperature was also considered a critical parameter, largely on the basis of experience with near fatal hyperthermia in the Man-High balloon flights (ref. 8). Fortunately, its instrumentation was realizable. Body temperature was monitored on all Mercury missions through MA–8 with a thermistor rectal probe. In the last Mercury flight, which was of longer duration, an oral sensor was used for pilot comfort.

Finally, some measure of respiration was considered mandatory for safety monitoring. Volume and rate information was preferred, but rate alone was acceptable. The first Mercury flights used a thermistor mounted on the microphone pedestal in the pilot's helmet to obtain indications of breathing. The thermistor, heated electrically to 200° F, was cooled by the movement of air over it during inhalation and exhalation. This method did not give reliable respiration traces and was replaced by the impedance pneumograph technique for the last two missions (ref. 9), which provided satisfactory records. Also, as pointed out in chapter 7 of this survey, impedance pneumography reflects chest movement. From the standpoint of determining astronaut survival, indication of chest movements was more valuable than indication of air flow. Thus impedance pneumography provided a double gain. The "safety-oriented" variables measured during the Mercury flights are summarized in table 3.

In addition to this information, cabin environmental data (pressure, temperature, etc.) and voice communication with the astronaut were provided to the medical monitoring team. The physiological variables measured for Project Mercury were the minimum considered vital to ensure pilot safety and give some confidence in extending flight time. No measurements were taken solely to investigate man's reaction to spaceflight.

At the end of the Mercury flight series, NASA concluded that men could tolerate weightless spaceflight for periods up to 34 hours, and that while data from the onboard

*Both venous and arterial pressure were later measured by direct techniques in a chimpanzee flight (ref. 7).

TABLE 3.—*Primary Safety Monitoring Variables for Space Flight Medical Monitoring*

Physiological variable	Bioinstrumentation		
	Mercury	Gemini	Apollo
ECG waveform	2 leads[a]	2 leads[a]	1 lead
Respiratory waveform	Thermistor[a] impedance pneumograph[a]	Impedance pneumograph[a]	Impedance pneumograph
Body temperature	Rectal probe,[b] oral sensor[b]	Oral sensor[b]	Oral sensor[b]
Arterial blood pressure	Arm cuff and microphone[a]	Arm cuff and microphone[a]	Arm cuff and microphone[b]

[a] Telemetered to ground stations.
[b] Onboard measurements.

biomedical sensors showed changes, these "abnormalities" could be considered normal physiological responses in the particular flight situation (ref. 9).

It must be emphasized that evaluation of the astronaut's physiological response utilized several information sources in addition to the telemetered physiological variables. These sources included control baseline data, voice responses in flight, answers to debriefing questions, and the detailed postflight physical examination. In fact, postflight detection of orthostatic hypotension (a radical drop in blood pressure and rise in heart rate following upright tilt) in the last two Mercury missions provided the primary indication of a potentially serious medical problem. This problem, termed "circulatory deconditioning," had also been observed by the Russians. It caused some apprehension about the 14-day exposure planned in the upcoming two-man Gemini flights and was a significant medical finding of the Mercury program.

GEMINI PROGRAM PLANNING

The Mercury safety monitoring philosophy was carried over to the Gemini program, which involved two-man astronaut teams and much longer flights. The same four parameters, namely, electrocardiogram (two leads), respiration, body temperature, and blood pressure, were measured continuously on both command pilot and pilot (see table 3). The most significant difference was the improvement in packaging and system design, and the addition of an onboard biomedical recorder.* On Mercury, only the biomedical sensors were located within the pressure suit. From the sensors, wires passed out through a connector to signal conditioners packaged on plug-in, printed-circuit boards. With Gemini, the signal conditioners were miniaturized and mounted in pockets on the astronaut's undergarment (see fig. 13, chapter 4). The new arrangement minimized lead length from the sensors, improving the signal quality. In addition, the Gemini signal conditioners were completely redesigned to provide higher input impedance, higher common mode rejection, lower output impedance, higher accuracy, and greater stability.

Although no gross medical problems were encountered in the Mercury flights, NASA was concerned that circulatory deconditioning might prove a limiting factor to weightless exposure by reducing the astronaut's ability to withstand reentry acceleration stress. This concern led to a revision in the planned Gemini flight schedule. Flight durations were approximately doubled to 14 days (ref. 10). It also led to a change from pure safety monitoring equipment to inclusion of medical experiments designed to reveal more subtle body changes. The Gemini experiments and their associated bioinstrumentation are summarized below.

Experiment M–1—cardiovascular conditioning—No onboard instrumentation utilized. Pre- and postflight tilt tests were used to judge efficacy of inflatable occlusion leg cuffs.

Experiment M–3—in-flight exercise-work tolerance—Heart rate and blood pressure response to exercise measured with safety instrumentation.

Experiment M–4—in-flight phonocardiogram—A piezoelectric microphone was used in conjunction with ECG signal conditioner and simultaneous ECG and phonocardiogram signals were obtained from each pilot and recorded on the biomedical recorder.

Experiment M–5—bioassays of body fluids—No onboard instrumentation utilized. A urine sampling and volume measuring system introduced a fixed quantity of tritiated water into each voiding. A sample of each voiding was taken after adding the isotope. Upon recovery, total volume was calculated by measuring the dilution of the tritium in the sample. Plasma samples were taken postflight.

Experiment M–6—bone demineralization—No onboard instrumentation utilized. Pre- and

*Developed for NASA by Cook Electric Co., this miniature unit contained seven data channels and provided a total record time of 100 hours. It combined an extremely slow tape speed (0.0293 inch per second) with no sacrifice of frequency response in the biomedical data channels.

postflight radiographs were made of the left foot in lateral projection and of the left hand of each crewman to determine changes in bone mass and density.

Experiment M–7—calcium and nitrogen balance—No onboard instrumentation utilized. Continuous data on dietary intake of each constituent under study and continuous collection of all urine and stool specimens were obtained before, during, and after flight.

Experiment M–8—in-flight sleep analysis—Two channels of electroencephalograms (EEG) were measured using two pair of scalp electrodes, two signal conditioners, and the onboard biomedical recorder.

Experiment M–9—human otolith function—Utilized an onboard vision tester to determine disorientation.

It is significant from a systems design standpoint that only two of the Gemini experiments utilized bioinstrumentation in addition to the safety instrumentation. These were the phonocardiogram experiment (which in fact utilized the Gemini ECG signal conditioner plus a specially developed microphone) and the EEG experiment, which used an entirely new signal conditioner. Thus the safety instrumentation was able to serve multiple functions in the spaceflight program.

APOLLO PROGRAM PLANNING

Since approximately 2000 man-hours of spaceflight had revealed fewer hazards and deleterious effects than anticipated (ref. 11), the Apollo safety bioinstrumentation requirements relaxed somewhat the previous requirement for continuous and comprehensive monitoring. The Apollo program increases the flight team size to three with its main objective a lunar landing and return. Approximately the same measurements will be made on Apollo as on Mercury and Gemini, but at less frequent intervals, and for only one of the three astronauts at a time. Exceptions will be during the Extravehicular Activity (EVA) and Lunar Excursion Module (LEM) mission phases. At these critical times, medical safety information transmission will be continuous, although even fewer variables will be measured. The change in Apollo information requirements was made because the successful 14-day Gemini flight was considered adequate qualification of man for the shorter (but admittedly more arduous) 8-day lunar mission, and communication will be more difficult from Apollo because of antenna orientation problems, distance, lunar shadowing, etc.

The safety bioinstrumentation planned for the Apollo lunar missions is summarized in table 3. During EVA and operation of the LEM, physiological safety monitoring will consist of only one ECG lead, the sternal. Additional information will be available from the voice communication and spacesuit environmental data channels. There is no current provision for onboard recording. Although the Gemini recorder functioned well, the general approach was compromised by two design factors: (1) lack of a "dump" capability, to permit data examination during the mission; and (2) difficulty in converting the necessarily specialized recording mode of the ultra-low speed recorder to normal formats for subsequent computer analysis. To NASA, these disadvantages were enough to offset the advantage of obtaining biomedical data in the intervals between telemetry acquisitions of Apollo data. Originally, a number of medical experiments were planned for Apollo. Some repeated those of Gemini, while others were new, such as vectorcardiogram and thoracic blood flow (cardiac output). These may be flown on a subsequent Apollo Applications Program.

ADVANCE MEDICAL PLANNING

Early in its consideration of manned spaceflight beyond Apollo, NASA initiated a multiphase program to plan the associated medical investigations. In Phase I of this program, NASA sponsored two studies (conducted by North American Aviation, Inc., and Republic Aviation Corp.) that were entitled "Biomedical and Human Factors Requirements for a

Manned Earth-Orbiting Station." These studies, completed in late 1963 (refs. 12 and 13), were a first attempt to specify the requisite measurements for a comprehensive scientific study of man's reaction and adaptation to the space environment, and to provide a preliminary conceptual design of instrumentation to accomplish the research. Compared to the spartan requirements of Mercury, Gemini, and Apollo, the proposed measures and their implementation were imposing, involving a spaceborne clinical laboratory, an onboard centrifuge facility, and a radiology laboratory. In general, the studies considered all possible laboratory techniques which could be useful and could possibly be implemented. Out of these studies came a number of novel instrumentation concepts. Typical were several ingenious methods of measuring body mass in a weightless environment, as well as new techniques of miniaturized clinical analysis.

Phase II of the program was a study conducted by Lockheed Missiles and Space Co. in response to a NASA Work Statement, which condensed the broad results of the Phase I study into a practical list of desired measures and asked that their conceptual implementation be related to specific vehicle configurations (ref. 14). Completed in early 1965 (refs. 15 through 19), the report constituted a detailed "Study of Conceptual Design and Optimization of Measurement Devices for Biomedical and Human Factors Testing for Orbital Research Laboratory Techniques." Phase III of the program (also conducted by Lockheed) was a time line study of the Apollo–X configuration, in which the various medical measurement procedures were "walked through" under terrestrial conditions. This work was completed in early 1966 (ref. 20).

The fourth phase of the effort is currently in progress. NASA has selected two contractors (Lockheed and General Electric) to define and optimize an integrated medical and behavioral laboratory measurement system (IMBLMS). This system will provide the capability of conducting long-term experiments utilizing orbital workshop vehicles. The laboratory will be designed to provide growth potential to conduct medical experiments through early 1970.

Paralleling the broad studies outlined above, "single-shot" planning efforts have been conducted periodically by NASA and its consultants (ref. 21). In addition, a number of experiments have been independently proposed by specialists in universities and in other goverment agencies. These are generally quite specific (e.g., the effect of prolonged spaceflight on carotid baroreceptor reflexes and arteriolar reactivity). During Phases II, III, and IV of the above-mentioned study, participating designers attempted to: (1) verify the associated equipment requirements of these specialized studies; (2) to maximize interchangeability of components; and (3) to minimize complexity, weight, and volume. The hardware called for in these planning studies remains to be developed. The interested reader may consult references 15 through 19 for details of the conceptual designs.

As NASA began the Apollo flights, new concepts of bioinstrumentation were evolving. This was especially true in the areas of data processing and display but also true at the level of basic physiology. For example, subsequent to Gemini VII, NASA evaluated a combinatory physiological parameter which included respiration rate, respiration depth, and rate of change of heart rate. Excellent correlation was found between this measure and estimates of pilot alertness obtained from EEG records. NASA envisions that this kind of effort to reappraise physiological information sources will lead to predictive indications of man's ability to extend his time in spaceflight. It matches NASA's simultaneous efforts to adapt its central biomedical monitoring system to the general needs of predictive monitoring (see chapter 5).

BIOINSTRUMENTATION SPECIFICATION AND ACQUISITION

As illustrated by the Mercury program, space monitoring systems often represent a compromise between information requirements and technical limitations. Once it is decided

what to monitor, however, a scientifically acceptable bioinstrumentation package must be produced in time to meet mission schedules. NASA has developed procedures to accomplish this task, based on fundamental principles of engineering planning, and the special requirements of biomedical and space operation. Some of these procedures are presented in the following section, not as a manual, but as a guide to similar planning in other situations.

The bioinstrumentation package for each spacecraft mission is made up of equipment from three categories of need. These are:

(1) Equipment required to measure information requirements originally selected as part of the space program.

(2) Instrumentation required to gather information on specific events determined necessary to fulfill the spacecraft mission, but not considered at the onset of the space program.

(3) Instrumentation associated with basic scientific questions, or with the advancement of instrumentation technology.

The first category is the more typical, and the flow chart presented in figure 1 illustrates most of the major planning elements and decision processes required to provide bioinstrumentation for measuring variables selected early in mission planning.

Because of the shortage of space and weight allocations on spacecraft and the cost of bioinstrumentation, system components should serve multiple functions where possible. This process is illustrated by the use of the safety bioinstrumentation in the Gemini experiments. It is being repeated in the acquisition of the Apollo Biomedical Experiment Systems. Sensors, signal conditioners, and voltage converters are shared among experimental setups for examining such variables as cardiac output by the Kubichek thoracic impedance technique (ref. 22), and the vectorcardiogram by the Frank lead network. Previously, the ECG signal conditioner (see chapter 4) proved particularly adaptable to multiple use. Its fundamentally broad frequency response and high gain make it an excellent general-purpose amplifier, suitable for phonocardiogram and even EEG recording with little or no modification.

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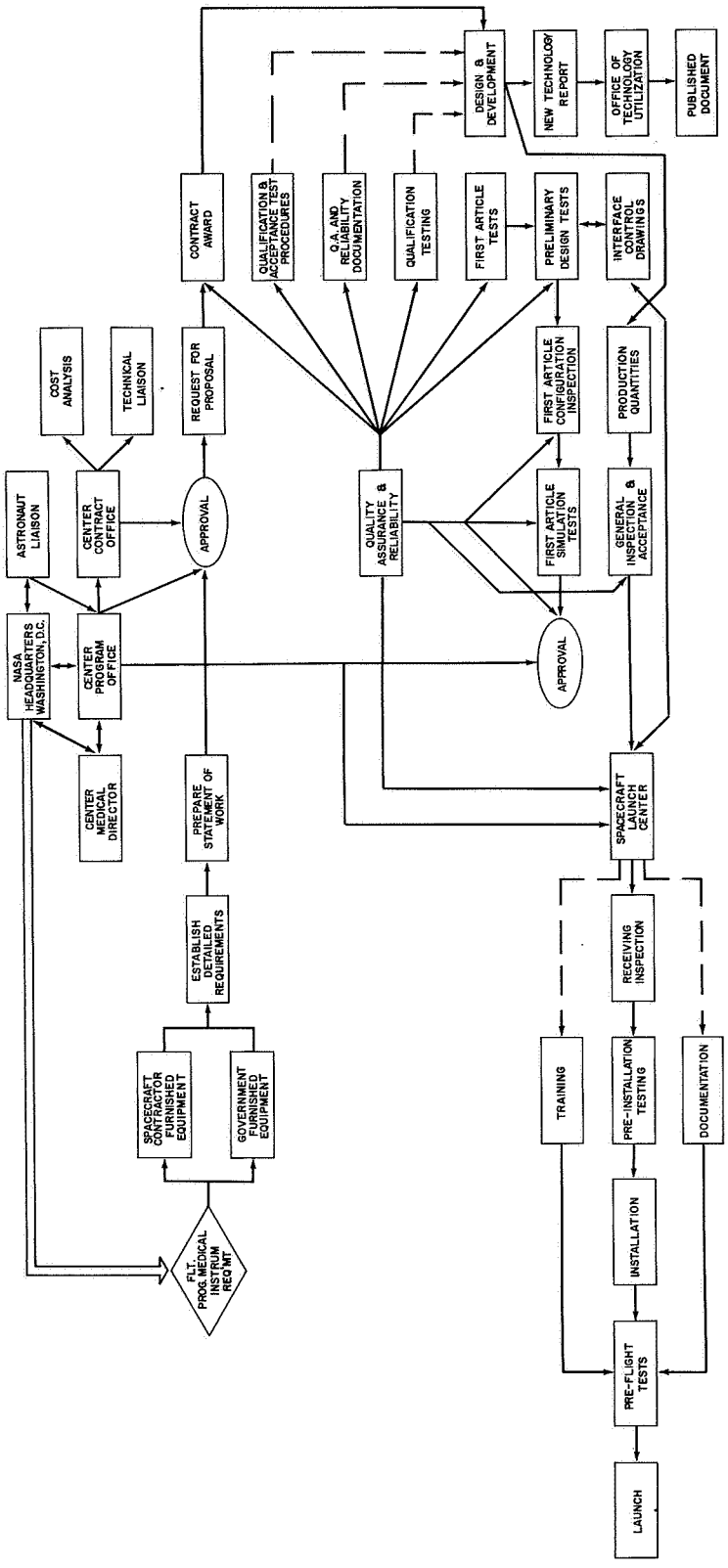

FIGURE 1.—NASA procedures for planning and development of originally specified bioinstrumentation.

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CHAPTER 3

Sensors and Sensor Attachment

The bioinstrumentation sensor, as discussed in this chapter, includes those sensing elements that transduce or transform energy from one form to another (such as a temperature-sensing thermistor), and those devices that make energy available for measurement (such as the voltage-sensing ECG electrodes). A number of major technological advances in bioinstrumentation sensor development and sensor attachment techniques have resulted from NASA spaceflight programs. Particular attention is paid in this chapter to ECG electrode construction details, ECG electrode attachment techniques, and EEG electrode development. Additional information is included to illustrate NASA approaches to other sensor problems in bioinstrumentation systems.

ECG ELECTRODES: DESIGN CONSIDERATIONS

In its simplest form, an ECG electrode consists of a metal plate contacting the skin through a layer of conductive paste. The primary requirements of a surface electrode for long term monitoring are (1) secure mechanical attachment and (2) reliable electrical contact.

In terms of metal-paste electrode systems, these requirements can be met by ensuring that (1) the electrode assembly does not become detached from the skin and (2) the conducting paste does not dry.

Thus, the primary design problems involve the "electromechanical" configuration of the electrode assembly and the adhesive techniques used to seal it to the skin. There are also a number of very important secondary design problems affecting the quality of the bioelectrical information received from the electrodes and the reaction of the subject's skin to the electrodes and attachment substances. If these problems are not overcome, electrical noise can reduce or destroy the usefulness of the signals received; or, discomfort, coupled with danger of infection, may require the subject to remove the electrodes before the end of the mission. More significantly, discomfort can interfere with his ability to carry out assigned tasks during the recording period. Included among the secondary design criteria affecting signal quality are:

(1) No electrode polarization; the electrode must exhibit a total reversibility of measured potential with a reversal of current.

(2) Low contact resistance between the metallic electrode unit and the living skin surface.

(3) No spurious signals generated within the electrode assembly during vibration, mechanical contact of spacesuit, etc.

In addition, on the medical side:

(1) No damage to the site of electrode application during the recording period.

(2) No noticeable discomfort while wearing the electrode assembly.

(3) No cumulative toxic effects caused by repeated electrode application; and no delayed effects caused by long-term contact.

These conditions are difficult enough to meet for recording under laboratory conditions. They become formidable during uninterrupted recording periods of several days in spaceflight

environments—for example, when the astronaut must remain in his spacesuit, active and sweating.

SPACEFLIGHT ECG ELECTRODES

When NASA began a development study of electrodes for electrocardiographic recording in space, many clinical techniques were available, each with its particular advantages and disadvantages. NASA concentrated on those electrode systems that had been developed specifically for monitoring the status of active subjects. An electrode development program was conducted both at McDonnell Aircraft and at the NASA Manned Spacecraft Center (ref. 1). Extensive tests were performed with human subjects, and particular attention was focused on the skin-to-electrode resistance. The results indicated that the fluid-filled electrode was most readily adaptable for flight use.

The basic principle of the fluid-filled electrode is isolation of the electrode from the skin by use of a conductive paste to provide the skin-to-electrode electrical path. This configuration greatly reduces spurious signals caused by relative movement between the electrode and the interfacing electrolyte.

The fluid electrode developed for Project Mercury by NASA (shown in fig. 2) consisted of a ring of molded RTV silicone rubber that supported a disc of 40-mesh, stainless-steel screen. A piece of small-diameter coaxial cable passed through the side of the ring, with the central conductor soldered to the screen. After application, the electrode formed an open cavity sealed to the skin (usually with an adhesive such as Elastoplast or its equal). Supported in the center of this cavity (but not touching the skin) was the stainless-steel screen which electrically contacted the skin via an electrolyte filling the cavity. After the addition of the electrolyte, the open end of the cavity was covered with a moisture-proof tape. These electrodes appeared to give less background noise than the standard clinical metal plates. There was also less baseline shift when the region of attachment was actively moved.

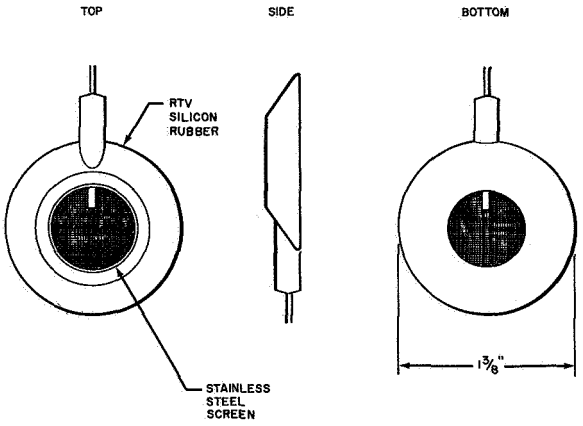

FIGURE 2.—Project Mercury ECG electrode.

During the Mercury flights, the monitored ECG signal was found objectionably susceptible to movement artifact (ref. 2), probably due to polarization of the stainless-steel-mesh electrode. Also, the soldered junction of the copper lead to the mesh screen was found to cause spurious signals and unwanted noise because of electrolytic action of the dissimilar materials. Modifications were made to the Mercury electrode design to circumvent these problems for the Gemini flights.

The improved Mercury electrode (fig. 3) was fabricated from a pure silver disc. Holes drilled in the disc permitted mobility of the electrolyte (achieved with the stainless-steel mesh in the Mercury unit). Again, the electrode lead was soldered to the disc; however, the soldered junction in this case was effectively insulated with a coating of epoxy. After attachment of the lead, the disc was anodized in a solution of sodium chloride to produce a thin, smooth coating of silver chloride (ref. 3). The RTV silicone rubber electrode housing supported the silver disc in a circular groove which maintained the disc above the skin. Electrodes fabricated in this manner were found to reduce greatly the noise effects experienced in the Mercury flights. This improvement can be attributed to the silver-silver chloride disc which provides an electrochemically reversible (i.e. nonpolarizing) electrode. The epoxy-protected solder junction served to reduce spurious signals.

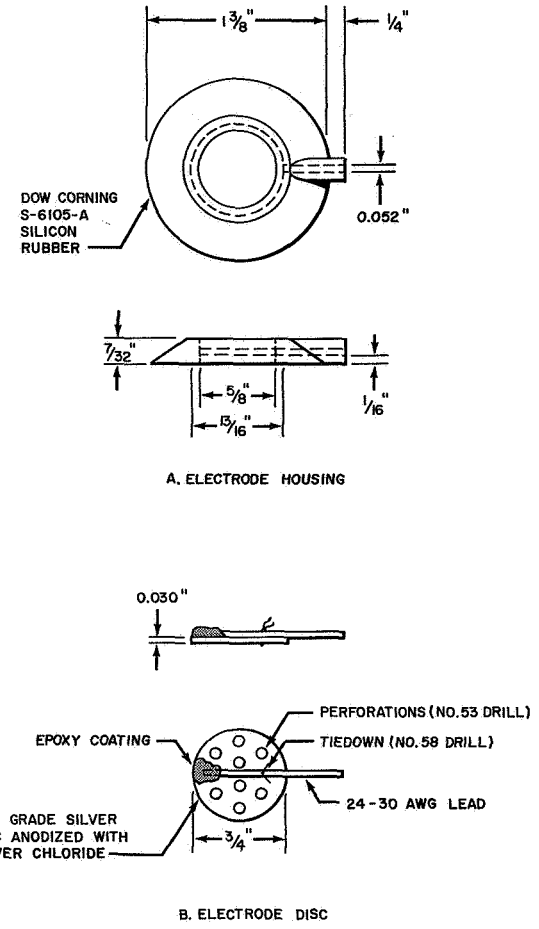

FIGURE 3.—Improved Mercury ECG electrode.

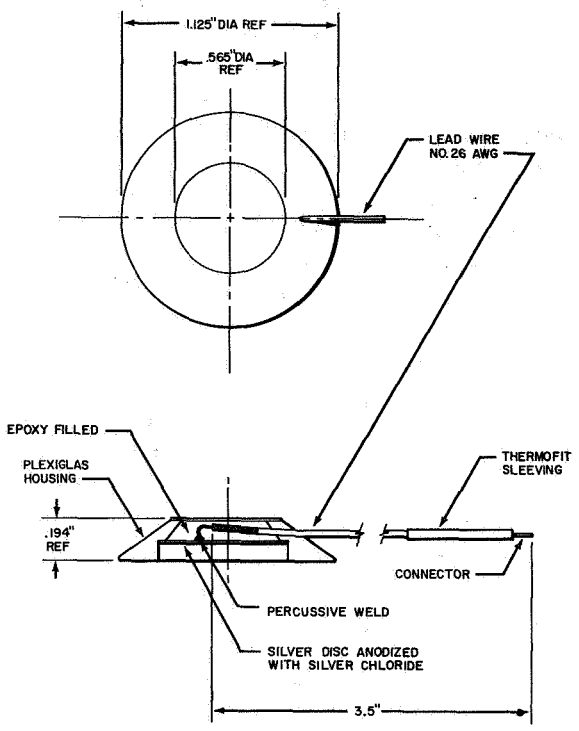

FIGURE 4.—Apollo ECG electrodes.

Electrodes developed for the Apollo flights are markedly different from those developed for earlier flights (ref. 4). The more important changes include the use of a rigid plastic cup to house the silver-silver chloride electrodes and the elimination of all soldering. Construction details of the Apollo electrode are shown in figure 4. Each electrode consists of a Plexiglas type VS 647–10 housing, a silver electrode disc, a wire lead, and a connector. The silver disc is coated with a thin deposit of silver chloride, applied by the technique developed for the Gemini electrodes. The lead consists of a length of clear, 26-gage, Teflon-coated copper wire percussively welded to the electrode silver disc and the electrode connector. This welding process completely precludes lead contamination, a situation to be guarded against when soldering dissimilar metals. After the lead is attached to the silver disc, the disc is sealed to an inner shoulder of the electrode housing, and the top cavity is filled with epoxy. This encapsulates the backside of the disc, the wire junction, and a short length of the lead wire. The result is an electrode which is electrically reversible (i.e. nonpolarizing), rugged, small, and much easier to apply than the Mercury and Gemini electrodes.

ELECTRODE PASTE

After many investigations of standard ECG electrode pastes, NASA determined that the hypertonic nature of these electrolytes (having a greater osmotic pressure than the skin) caused objectionable irritation when applied for more than about 24 hours. Consequently, NASA developed a paste for the Mercury program that produced no irritation after more than 48 hours of use. In addition, it was slow-drying, had a high viscosity, and would main-

tain electrical resistance stability. The paste was a modified bentonite compound (aluminum silicate powder) consisting of 15 grams of bentonite, 10 cc of water and 3 grams of calcium chloride, and was used on the early Mercury flights (ref. 1).

Later Mercury flights used a further refinement, a 10-times isotonic concentration of Ringers' physiological solution, thickened with Carbopol.[1] This paste also includes 0.1 percent propyl-p-hydroxybenzoate as a preservative to prevent deterioration from biological contamination. Subsequently, the thickening agent was changed from Carbopol to a mixture of Natrosol[2] and PVP,[3] which simplified formulation of the paste and provided a nonirritating, nonsensitizing electrolyte. These pastes were tested on more than 50 subjects with application times up to 7 days (ref. 5) and were found to be completely compatible with the long-term monitoring requirements of the Gemini and Apollo missions.

ECG ELECTRODE APPLICATION

An improved method for applying the NASA ECG electrodes was evolved during Project Mercury, and excellent results were obtained using this technique for attachment and sealing. The procedure, if performed by an experienced technician, allows attachment of the Mercury and Gemini-type electrodes in about 3 minutes.

The skin is first lightly swabbed with acetone or an ether-acetone mixture. (Any undesirable hair is removed by shaving, using care not to damage the skin.) A ring of Stomaseal[4] tape is applied to the flange of the electrode housing. The electrode is then filled with electrode paste from the front (using care not to get paste on the tape or the back of the housing) and pressed to the cleansed skin. Next the back of the electrode housing is filled with paste and the opening covered with a 1-inch square of Mystic[5] tape. A 3-inch square of Micropore[6] is then applied to cover the entire electrode after the electrode lead is dressed to the desired position. Electrode resistance will vary at application from about 100 to 5 kilohms and will drop in approximately 1 hour to 50 to 2 kilohms. If extremely low electrode resistance is required, the technique of decornification or skin drilling (ref. 6) may be used to provide resistances of 1 to 5 kilohms, which will remain at this level for at least 48 hours. Upon removal of the electrodes, the skin is washed with Zephyran chloride and an antiseptic skin lotion applied to prevent irritation or infection.

The procedure for applying NASA's Apollo electrodes is somewhat different in that the paste filling is done in one step instead of two. Since the Apollo electrode has an open front and closed back, the electrode is filled approximately two-thirds full after the Stomaseal is applied to the electrode. Then the electrode is pressed to the skin and covered with a 3-inch diameter piece of Micropore tape. (The closed back eliminates the need for the Mystic tape.)

ECG ELECTRODE PLACEMENT

Choice of the anatomical sites for ECG electrode placement was made by NASA after extensive investigations of the ease, convenience, validity, and reliability of signal sensing for various lead configurations (ref. 7).

The original Project Mercury ECG electrode scheme included three electrodes for two ECG leads, with one electrode common to both measurements. However, to make both measurements completely independent, the three-electrode system was changed to four. The electrode sites chosen are illustrated in figure 5; they were the bilateral mid-axillary line (electrodes 1 and 2) and the anterior midline of the episternal area (electrodes 3 and 4). The axillary lead consisted of one electrode placed at the base of the rib cage on the

[1] Carbopol 940 (B. F. Goodrich).

[2] Hydroxy-ethylcellulose-Natrosol 250 HR (Hercules Powder Co.).

[3] Polyvinyl pyrrolidone K–90 (General Aniline Corp.).

[4] Washer-shaped, double-sided adhesive mounting discs cut from Scotch No. 1500 Stomaseal (Colostomy) tape.

[5] Mystic Silicone Tape No. 7010.

[6] Scotch Micropore Surgical Tape No. 530.

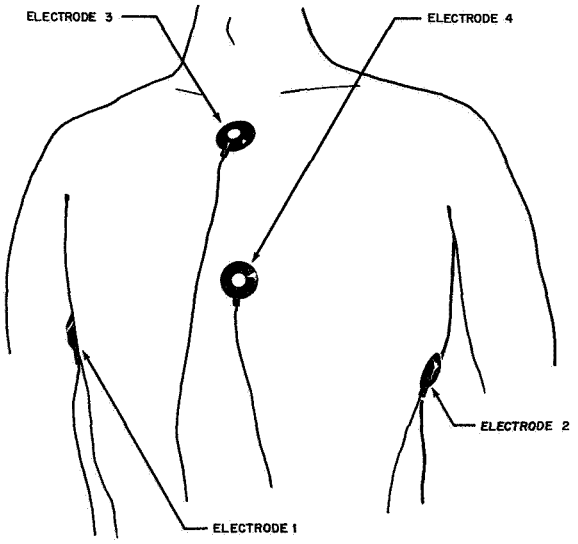

FIGURE 5.—Anatomical placement—Mercury ECG electrodes.

right side with the left electrode placed on the rib cage at the third intercostal space. The sternum lead was roughly at right angles to the axillary lead, with one electrode placed on the manubrium and the other at the xiphoid process. The choice of these sites was based on the following factors:

(1) The sternum has very little underlying muscle tissue and thus reduces the possibility of electromyographic artifact effects.

(2) The intercostal (rib) muscles also generate very small electromyographic potentials, even with rather violent activity.

(3) The data from these two lead configurations correlate very well with traditional data from standard ECG leads.

The axillary lead was found to be additionally useful when, in later Gemini flights, the impedance pneumograph was used for extracting respiration data. The impedance pneumograph requires one set of electrodes across the thorax at the mid-axillary line, and at the sixth or seventh intercostal space. Development of compatible electronics allowed the impedance pneumograph and ECG amplifier to share the same set of electrodes. Hence, minor relocation of the axillary electrode pair permitted two completely different physiological measurements to be made simultaneously from the same set of electrodes.

EEG ELECTRODES

NASA is currently engaged in the development of an improved system for obtaining the EEG of pilots and astronauts performing tasks under stress. In most applications, EEG electrodes have been cemented to the scalp; they are uncomfortable, irritate the scalp, and take as long as an hour to attach. This technique was used on pilot Frank Borman on the Gemini VII mission. The electrodes consisted of chlorided silver discs imbedded in small plastic cups. The cups were filled with an electrode paste and attached to the scalp with Eastman 910 adhesive over sites which had first been denuded with depilatory cream and lightly drilled with a high-speed dental burr to break the skin surface (ref. 8).

In addition to the problem of comfort and the time-consuming attachment technique, these electrodes also required that the lining material of the astronaut's helmet be designed with indentations to avoid pressure on the electrodes. The flight data showed that good quality EEG tracings were obtainable with this technique for relatively long periods of time. (One of the two EEG channels provided some useful data up to the 54th hour of flight; ref. 8.) However, in summarizing the EEG experiment of the Gemini VII flight, Maulsby states that "it is hoped that a longer-lasting electrode system can be developed in the near future . . ." (ref. 9).

A novel EEG electrode system, which consists of nonirritating sponge-type electrodes mounted in the subject's helmet, shows promise of meeting this aim. The main development objective is to produce an electrode configuration that can be put on and removed by the astronaut in the course of donning and removing his helmet without any special attachment to the scalp or parting or removal of hair. Early investigations of the sponge-type EEG were conducted, partially under NASA support, at the UCLA Brain Research Institute (ref. 7) and resulted in the configuration shown in fig-

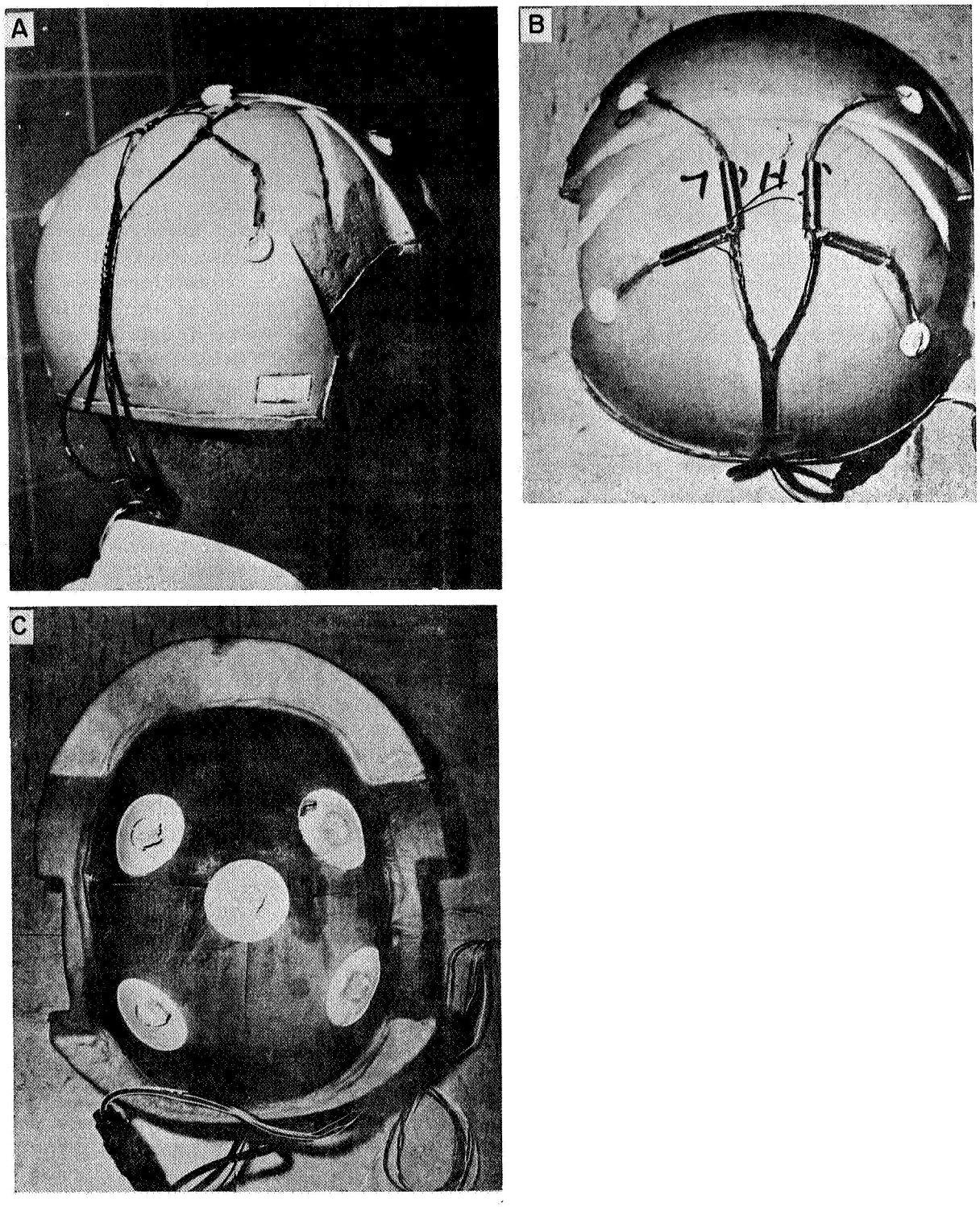

FIGURE 6.—Early helmet-mounted sponge electrode and preamplifier system, developed at the Brain Research Institute, UCLA.

ure 6. Preamplifiers in the form of small cylinders were imbedded in the helmet liner. A short input lead made connection with a stainless-steel wire, which, in turn, contacted a sponge soaked in a nonirritating electrolyte. A silicon rubber grommet was molded to fit an aperture in the liner and served to preserve the liquid. When the liner was placed on the head with no preparatory cleansing of the scalp, satisfactory contact developed within a few minutes. The contact developed more rapidly if electrode paste was lightly applied to the scalp, but this was not essential.

Further developments by the Brain Research Institute produced the electrode system shown in figure 7. The configuration is unique in that a simple tin electrode in a stannous chloride electrolyte eliminates the common problem of electrolyte-metal movement artifact. The electrolyte and tin electrode are encased in a semipermeable ceramic shell which is, in turn, surrounded by the scalp-contacting sponge material (A). The ceramic cups are prepared by machining commercially available hydrous magnesium silicate rods to the required dimensions and then firing to the desired hardness. An epoxy flange is molded in place onto the cylindrical cup. A separately molded silastic rubber cap is used to hold the tin wire in place

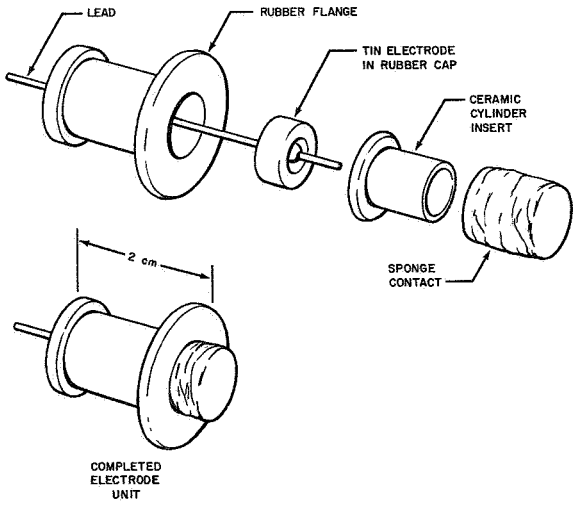

FIGURE 7.—Improved BRI helmet-mounted EEG electrode.

inside the cup (B). Contact between the scalp and the electrode is established by a cylindrical cellulose acetate sponge, which is hollowed at one end to accept the ceramic cup assembly (C) and (D). The sponge is housed in a silastic rubber flange assembly, which provides a means of attaching the electrode to the helmet and serves to contain the electrolyte in the sponge. The sponge protrudes about 7 mm from the flange to ensure good contact with the scalp. It is wetted with a physiologically compatible electrolyte such as saline, ⅓ N KCL or Ringer's solution containing polyvinyl-pyrrolidone as a thickening agent. No special preparation of the scalp is required, except for the removal of oils from the hair and skin at the contact site. NASA is currently supporting[7] further development of this type of electrode with an integrated preamplifier for use in the Apollo program.

A similar concept in sponge-type electrodes has been developed by NASA at its Ames Research Center (ref. 10). The Ames electrodes are part of a complete EEG telemetry system mounted entirely in a flight helmet. The system includes amplifiers, a battery-powered wireless transmitter, and the sponge-type electrodes. The sponge electrode (fig. 8) consists of a flexible tip resting against the scalp and a rigid section that fits securely in the helmet. The flexible portion is a hollow-core cellulose acetate sponge impregnated with electrode paste. The rigid portion consists of a disc of fritted glass wetted with a saline solution, a disc of compressed silver powder, a disc of Ag–Ag–Cl, and a solid-silver amplifier contact. The cylindrical sponge portion of the electrode is slightly compressed when fitted to the subject; this provides light, steady compliance with the scalp. Except for the tips, the exterior of the sponge is coated with a thin layer of self-leveling silicone rubber. One of the tips extends 6 mm to contact the scalp. The rubber coating helps to retain moisture within the sponge; it also provides a small degree of stiffness so that the sponge can penetrate the hair. The sponge portion of the electrode system is disposable after use.

[7] Contract NAS 9–7832.

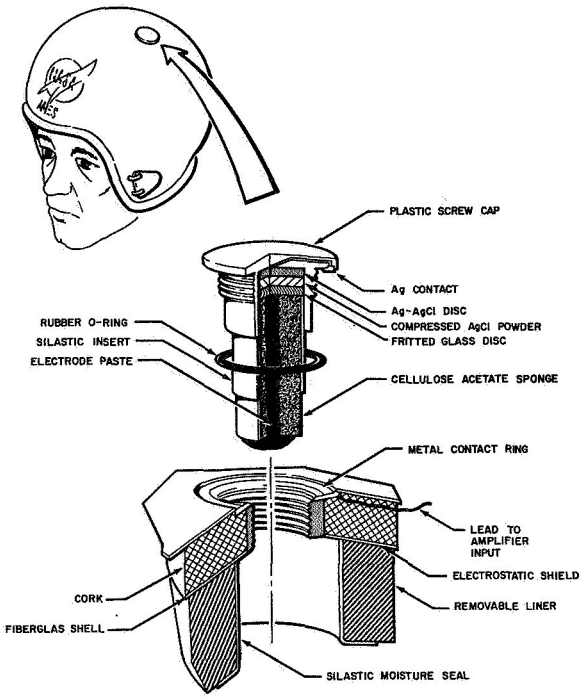

FIGURE 8.—Construction details—NASA/Ames helmet-mounted EEG electrode.

Extensive tests of this electrode system have been made during the last 2 years at NASA/Ames, including laboratory tests and tests on jet aircraft flights and centrifuge runs. These tests have demonstrated the feasibility of the concept. After one of the centrifuge runs, the subject was asked to remove his helmet for 5 minutes. Tests were resumed without making any adjustments to the helmet or to the electrodes, and there was no loss of data.

ADDITIONAL CONTRIBUTIONS: BODY TEMPERATURE SENSORS

NASA used two different types of body temperature sensors in the Mercury program: a rectal probe incorporating a thermistor sensing unit; and, later, a skin temperature probe consisting of a thermistor in a thermoinsulated disc (fig. 9). Both of these units were developed in NASA facilities. The rationale for using the rectal probe on Mercury flights and the results obtained are discussed in chapter 2 and reference 1.

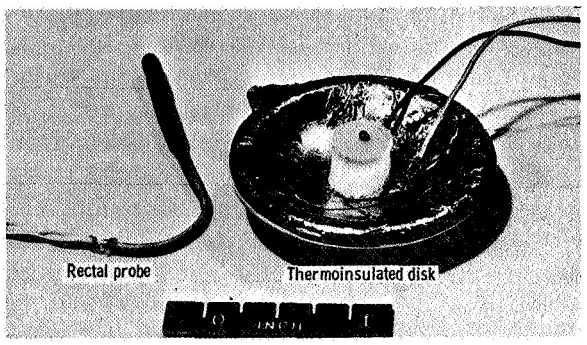

FIGURE 9.—Project Mercury body temperature sensors.

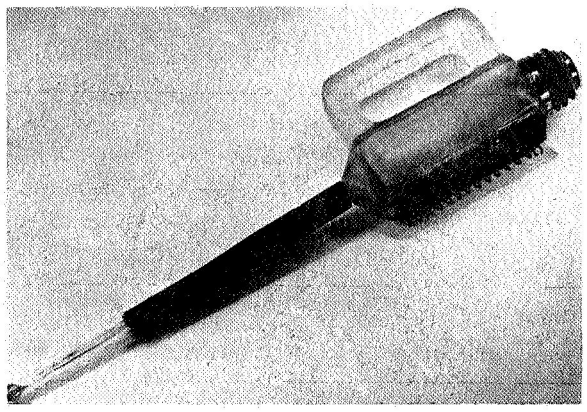

FIGURE 10.—Oral temperature sensor used in the Gemini flights.

For the Gemini flights, an oral temperature sensor [8] (fig. 10) was substituted for the rectal probe (ref. 2). This sensor consisted of a finger-formable Teflon-covered thermistor assembly attached to a small section of machined polycarbonate. The polycarbonate section contained a Velcro pad for easy attachment inside the astronaut's helmet. Preliminary tests showed it was difficult to hold the probe in the mouth because of the small probe diameter and the slick Teflon cover. This problem was eliminated by slipping a 5/32-inch diameter Neoprene sleeve over the Teflon-covered probe, leaving approximately ¾ inch of the Teflon exposed. Used with appropriate signal conditioning equipment, this oral temperature

[8] Developed for NASA by Spacelabs, Inc., Van Nuys.

probe covers the range of 95° to 105° F with an accuracy of 0.05 percent.

A new skin temperature sensor (fig. 11) was developed for the simulation chamber bioinstrumentation system used in the Apollo program (ref. 4). This sensor consists of a thermistor mounted at the center of a plastic support which serves to hold the thermistor against the skin with moderate pressure, provide good protection for the thermistor, and ensure ventilation and accurate skin temperature sensing. It is normally attached to the skin with a Stomaseal ring. Temperature measurement range is 80° to 115° F±0.3° using compatible electronics.

APPLICATION EVALUATION

NASA bioinstrumentation sensors and sensor attachment techniques have resulted in many technological advances which have direct applicability to clinical and research medicine. For example, the NASA-type electrode housing and attachment techniques have already been accepted by the medical community as a significant advancement in electrode technology. Various manufacturers offer a variety of electrode sizes and shapes based on NASA-initiated developments.

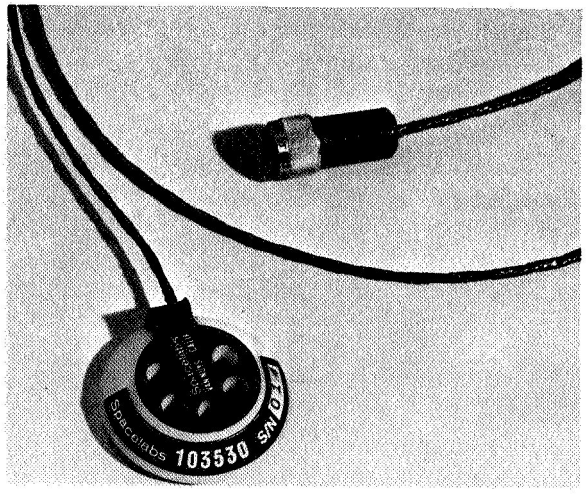

FIGURE 11.—Skin temperature sensor—Apollo space chamber simulation.

This transfer of NASA technology will undoubtedly continue because of the increasingly frequent use of bioinstrumentation for clinical patient evaluation and monitoring, and for medical, physiological, and psychophysiological research. ECG and EEG measurements are more and more becoming a diagnostic and an evaluative tool of the clinician. Consequently, the demands placed on the measuring devices have increased tremendously in terms of reliability, longevity, and patient comfort. NASA's improvements to sensor technology aid appreciably in meeting these demands. In its electrode fabrication, NASA has had to be extremely sensitive to such phenomenon as contaminant "out-gassing" at very low pressures, flammability in pure oxygen atmospheres, and the like. The resultant narrowing of material choices, in addition to the rigorous quality control procedures imposed on all space-qualified equipment (see chapter 8), naturally makes the NASA component expensive. But by relaxing those NASA restrictions that go far beyond normal medical needs, the functional improvements achieved by NASA over conventional sensors may be advantageously incorporated by the medical community at reasonable cost.

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CHAPTER 4

Signal Conditioning

In a bioinstrumentation system, the signal conditioner operates betwen the primary sensor and the processing and display units. Figure 12 illustrates the location of the signal conditioners in the Gemini safety bioinstrumentation system; the general arrangement is similar in most laboratory and clinical systems. Frequently, the signal conditioner is the "forgotten" element of the system. Sensors, transducers, and computation and display techniques generally offer the more obvious and intriguing design problems, leading to relative neglect of the intermediate conditioning function. Nevertheless, signal conditioning is fundamentally important because the signal conditioner largely determines the form of the biomedical information supplied to the system user, directly influencing his concept and interpretation of the underlying physiological processes.

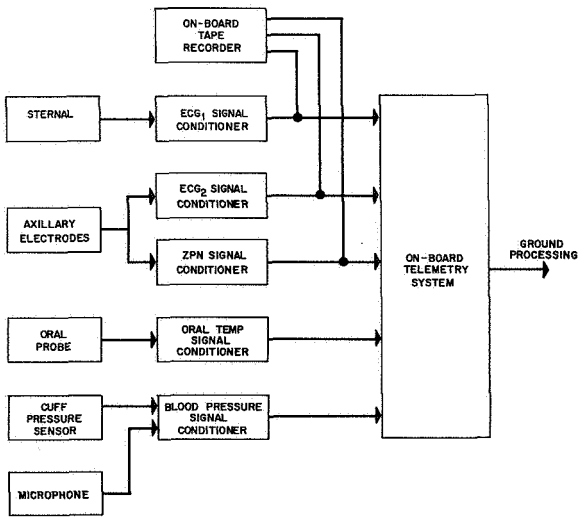

FIGURE 12.—Gemini safety bioinstrumentation system —one astronaut.

For example, early ECG recordings contained a broad baseline composed of 60-Hz noise. Physicians became accustomed to its presence, unconsciously accepting it as part of the signal. When improvements in signal conditioners eliminated this noise source, the "clean" ECG complex was rejected in several instances because it did not resemble textbook examples. However, the clean signal soon brought about greater appreciation of detail in the ECG waveform. This led to further improvements in signal conditioning, expanding the signal frequency bandwidth. Attention was then focused on other limiting elements in the system, such as the strip chart recorder. The inadequacies of this output unit promoted computer analysis of the ECG signals and reinforced what has become a major movement in clinical medicine.

In a more general sense, the designer must decide what is useful signal and what is noise at the level of the signal conditioner, particularly with respect to signal frequency components. The distinction between signal and noise is not always obvious. Often it is forced by bandwidth restrictions that act along with other interface constraints to shape signal conditioner design. This has been the case in NASA spaceflight. Only limited bandwidth is allowed the biotelemetry channels, and it must be apportioned among the various physiological signals. In fact, the bioinstrumentation

bandwidth allocation has decreased constantly from the Mercury to the Apollo programs, reflecting increased confidence of medical well-being in spaceflight and more efficient use of bandwidth. The reduction has necessitated a continual reevaluation of critical signal frequencies for each physiological signal source.

Even when bandwidth is not critical, the circuit designer attempts by filtering or other means to minimize noise and artifact, and perhaps to accentuate certain crucial aspects of the biomedical signal. His design rests on basic knowledge of the origin of the signal and awareness of its subsequent utilization in the system. Design conventions may change as new knowledge is gained; or a previously acceptable design may be reworked to meet new system requirements. For example, the optimum frequency range for the brachial pulse signal in automatic ausculatory blood pressure measurement is still an open question. And the change from a differential low level (10 MV) multiplexer on Gemini spacecraft to a single-ended high level (5V) unit on Apollo necessitated extensive circuit redesign of equivalent bioinstrumentation signal conditioners.

The functional boundaries of the signal conditioner can be difficult to define. The basic signal conditioner consists only of amplifiers and filters. In other cases it may include some computational elements, or serve as a telemetry transmitter. NASA spaceflight signal conditioners have been primarily the basic type, preparing the biological signal for telemetry (or onboard recording) and ground processing. As is shown in figure 12, the signal conditioners themselves are small separate packages worn by the astronauts under the spacesuit in a compartmented belt. Figure 13 shows the spaceflight units for Gemini along with the electrical harness assembly. Other NASA research, notably in the biotelemetry field, has led to development of highly advanced signal conditioners performing several functions in the bioinstrumentation system.

The three major examples presented in this chapter were chosen to illustrate distinct facets of signal conditioner design shared by NASA and nonaerospace programs. The units described are representative of specific problem areas in bioinstrumentation system development: (1) meeting rigorous performance specifications, (2) making a difficult measurement, and (3) providing sophistication along with miniaturization.

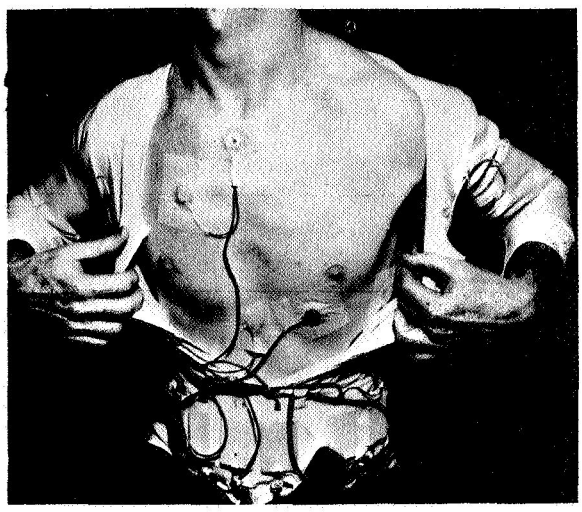

FIGURE 13.—Harness assembly for the Gemini signal conditioners.

APOLLO ECG SIGNAL CONDITIONER

The Apollo ECG signal conditioner [1] represents a system element designed to accomplish a well-defined task under exacting measurement conditions. It is the latest of three successively improved units supplied in turn for the Mercury, Gemini, and Apollo programs.

Early in its planning, NASA determined the requirements for electrocardiogram (ECG) signals from its astronauts in space (see chapter 2). These measurements, however, required almost entirely new equipment. Clinical measurements are typically made for only short periods in a stable environment on almost immobile patients. The clinician usually has direct access to the equipment and to his patient and could make adjustments or ask for subject cooperation during the recording session. Measuring active subjects continuously for

[1] Developed and fabricated for NASA by Spacelabs, Inc.

days and weeks in a spacecraft posed formidable problems. These were compounded by the need for the equipment to operate without adjustment.

In principle, ECG signal conditioning involves nothing more than amplification of a varying voltage obtained from surface electrodes. Ideally, the conditioner should amplify the signal without altering its characteristics while guarding against spurious signals, such as environmental interference and circuit noise. Noise from all sources may be reduced by limiting the band of frequencies over which the amplifier functions, taking care not to eliminate valuable components of the ECG signal itself. These steps do not reduce noise in the frequency band of the signal, nor affect the introduction of "unwanted" voltages from electrode movement or from extraneous fields. The sensors, the input leads, and even the subject's body may act as receiving antennas for the electrical and magnetic fields established by conductors carrying alternating current within the spacecraft. Two remedies may be employed to reduce the pickup effect: (1) shielding the input leads; and (2) using input circuitry which discriminates against unwanted signals. NASA's greatest contributions to the technology of signal conditioners for electrocardiography lie in the area of noise discrimination.

Figure 14 depicts schematically the Apollo signal conditioner's three differential amplifiers (ref. 1). Specifications call for an input impedance of greater than 40 megohms, a common mode rejection (CMR) ratio of greater than 100 000:1, a continuously variable gain of 600 to 4500, and an input noise level less than 5μV peak-to-peak. Both high input impedance and high common mode rejection are

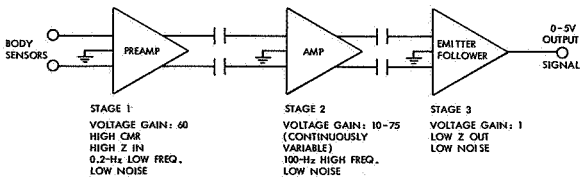

FIGURE 14.—Apollo ECG signal conditioner—block diagram.

extremely important to noise elimination, and both are unusually high in the Apollo unit.[2]

Figure 15 shows in detail how these high performance specifications were achieved in the preamplifier circuitry. The schematic shows a differential amplifier stage comprised of the dual transistors $Q1$, $Q2$, and $Q3$. These transistors, in effect, operate as two single transistors with an overall current gain $(\beta)_T$ approximating the product of the current gain of each of the three transistors $(\beta)^3$. This multiplication effect is reflected as an extremely high input impedance, which is negligible compared to the resistive network of $R1$, $R2$, and $R25$. These resistors then determine the input impedance, which is greater than 40 megohms.

The emitter circuits of the groups-of-three ($Q1A$–$Q2A$–$Q3A$, etc.) are fed by constant current sources $Q5A$ and $Q5B$, which serve in differential amplifier stages to increase the common mode rejection ratio and balance offset drifts. The 100-db common mode rejection ratio is achieved by careful matching of component characteristics. Minute variations in transistor properties exist, especially at the low collector currents in the preamplifier. These variations could have been balanced through inclusion of a potentiometer but, because of size and weight restrictions, the compensation was done by component selection. The packaging technique, required to fit the complex circuitry of the ECG signal conditioner in the small Apollo module container and to meet

[2] The input impedance of an amplifier is the ratio of the amplitude of the input voltage to the resultant current flow in the input circuit. The input voltage is developed across the input impedance and is at a maximum when the source impedance is negligibly low in comparison to the amplifier input impedance. Therefore, if the input impedance is not sufficiently high, attenuation and distortion of the recorded voltages may occur. Also, changes in the source impedances can be reflected as apparent output signals. In ECG measurements the source impedance is a function of the type of electrode used, and it is common to experience source impedance variations of thousands of ohms. The CMR of a differential amplifier is a figure of merit for reduction of in-phase/input signals caused by electrical field interference over out-of-phase signals caused by biological phenomenon. The greater the CMR, the greater the discrimination against extraneous noise.

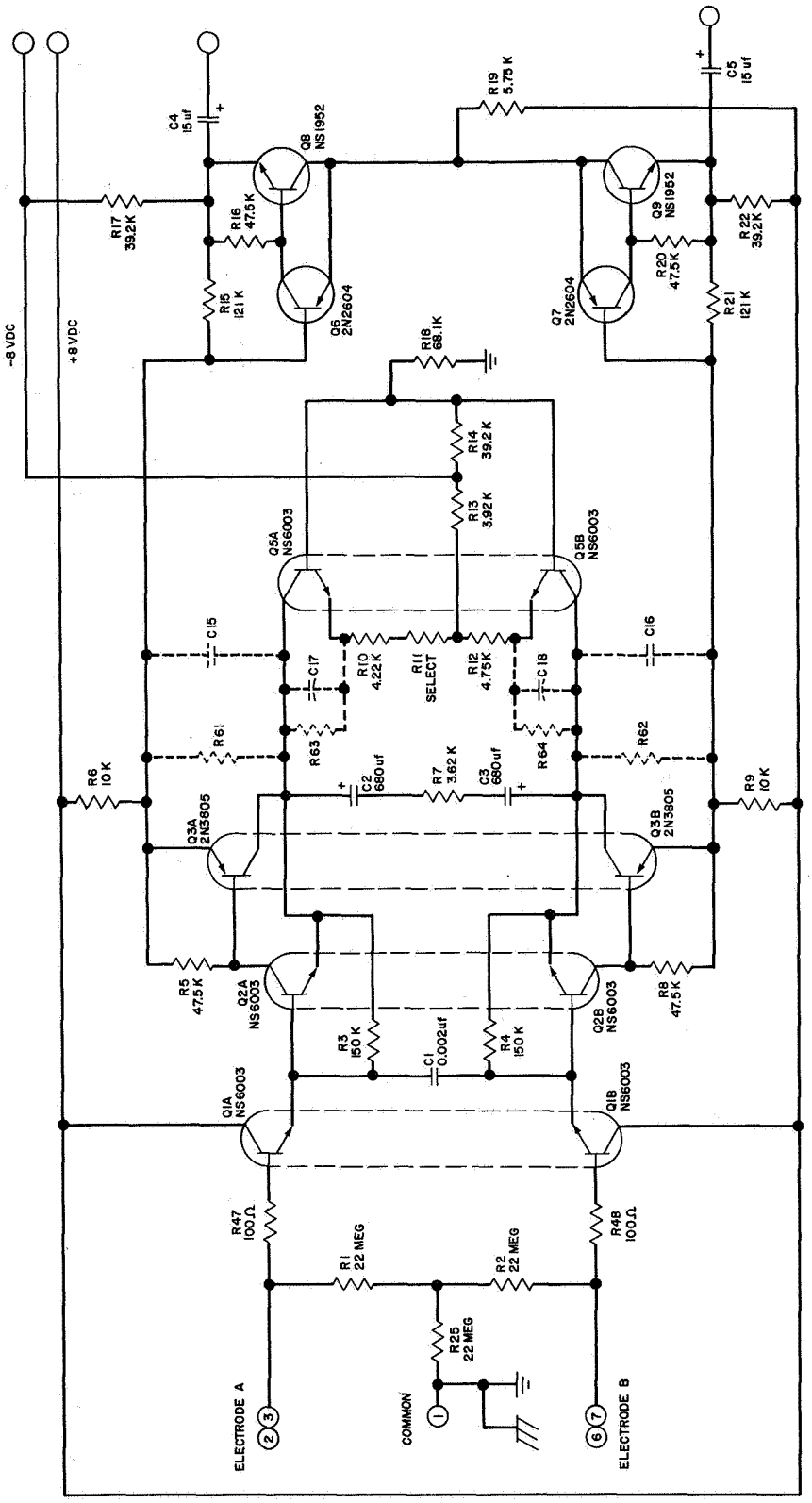

FIGURE 15.—Input circuitry—Apollo ECG signal conditioner.

simultaneously the rigorous environmental specifications, is described in chapter 8.

GEMINI BLOOD PRESSURE SIGNAL CONDITIONER

This section describes the spaceflight signal conditioner used to obtain indirect arterial blood pressure measurements during Gemini flights.[3] The design task was somewhat like that for the ECG unit in that a common clinical measurement had to be obtained under disadvantageous conditions. But in many respects, blood pressure measurement represented a more novel problem because the definition of indirect arterial pressure is not as well established as that of the ECG and because pneumatic and acoustic energies, along with electric signals, are involved in blood pressure measurement.

The value of arterial blood pressure as a summary cardiovascular measure is well known. Physiologists for many years have routinely measured the pulsatile arterial pressure at a number of sites by direct arterial puncture. While direct recording is ideally suited for experimental animals or humans under aseptic hospital conditions, its use in routine clinical examination is unacceptable. Instead, indirect sphygmomanometry is used. This method utilizes a pneumatic occluding cuff on the upper arm and a stethoscope or microphone downstream over the brachial artery. The cuff is inflated until flow in the artery is stopped and is then slowly deflated. Cuff pressure at the first appearance of sounds (called Korotkow sounds) over the artery is taken as systolic pressure (the highest pressure in the cyclic arterial pressure waveform). Cuff pressure when the sounds disappear is generally accepted as diastolic pressure (the trough of the arterial wave). Determination of these points requires some observation skill. While indirect sphygmomanometry yields only a small fraction of the information contained in a continuous record of arterial pressure, the great mass of clinical data obtained over the last 50 years provides a solid statistical basis for its use.

In the Mercury and Gemini programs, NASA decided to use indirect sphygmomanometry as the simplest and most practical method for obtaining a useful measure of arterial blood pressure in flight (ref. 2). Absence of a skilled observer or visual display devices required the pressure and sound information to be transmitted to ground stations for interpretation. With Gemini, the measurement was accomplished using the following components:

(1) An arm cuff specially designed for operation beneath the pressure suit.

(2) An inflation assembly consisting of a manually operated squeeze bulb and a bleed orifice to impose a constant cuff deflation rate.

(3) A microphone assembly consisting of a piezoelectric crystal and integral preamplifier.

(4) A signal conditioner containing the cuff pressure transducer and amplifier, a Korotkow-sound amplifier, and the circuit for mixing the dc pressure signal with the ac pulse signal.

Automatic cuff inflation devices had been planned but were not installed on the Mercury vehicle. Manual cuff inflation provided economy and reliability in the Gemini system. As pointed out in chapter 2, the Mercury and Gemini bioinstrumentation electronics were housed in the space capsule instead of within the space suit.

Figure 16 is a diagram of the Gemini flight system. Operation of the cuff was similar to the standard clinical device. Cuff pressure was measured by a pressure transducer, which

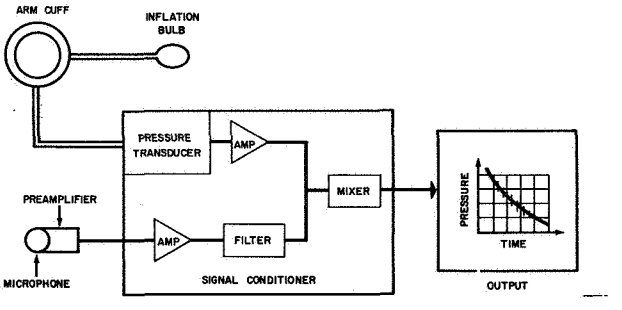

FIGURE 16.—Gemini arterial blood pressure measurement—block diagram.

[3] Developed and fabricated by the AiResearch Division of the Garrett Corp.

yielded a proportional dc output signal. At the appearance of the first Korotkow sound, an ac signal was superimposed on the dc output. The pressure corresponding to this first sound was taken as systolic arterial pressure. As the cuff deflated further, the sound signals increased in amplitude, then decreased until they finally disappeared. The pressure corresponding to the last observed sound was taken as diastolic arterial pressure. The trace on the right-hand side of figure 16 illustrates a typical recording produced by the system.

Figure 17 shows details of the Gemini blood pressure signal conditioner itself. Three major contributions to bioinstrumentation design were:

(1) *Miniature pressure transducer.* NASA supported an intensive effort by AiResearch Corp. to develop a solid-state semiconductor strain-gage pressure transducer (ref. 3).

(2) *Korotkow sound filtering.* The Korotkow sounds are processed by a narrowband filter in the Gemini system. According to its designer, the sound components between about 30 and 40 Hz undergo more clearly defined changes in amplitude when the arterial flow is occluded. Thus at these frequencies, the end points of the Korotkow sounds correspond more closely to systolic and diastolic arterial pressures.

(3) *Packaging.* A unique part of the design is the packaging of the cuff pressure transducer within the small (approximately 1.35 cubic inch) volume of the signal conditioner. A small tubular extension of the signal conditioner attaches to the cuff pressure line. A reference port admits suit pressure to one side of the strain gage transducer diaphragm to provide a gage reference. This addition was necessary because cabin pressure can change markedly during spaceflight.

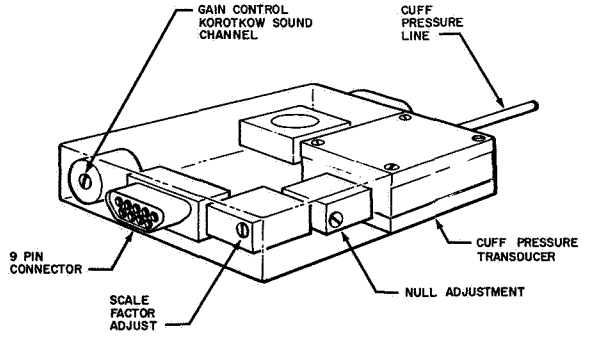

FIGURE 17.—Partial assembly—Gemini blood pressure signal conditioner.

Additional contributions included the elimination of one of the two amplifier filter sections in the pulse channel that had been required for Project Mercury. Moreover, the circuit was modified to reduce the required dynamic range of the gain control, its adjustment being virtually foolproof. The results of these improvements were a large savings in weight, size, and power consumption over the Project Mercury system. Specifications for the Gemini unit are shown in table 4.

TABLE 4.—*Signal Conditioner and Microphone*

Parameter	Value
Output ac section	15mY peak-to-peak pulse
Output dc section	0 to 20 mV corresponding to 50 and 250 mm Hg; linear within 1%; accuracy 1%
Output impedance	5000 ohms maximum
Power requirements	170 milliwatts maximum
Size	1.5×2.0×0.375 inches maximum
Weight	43 grams maximum (signal conditioner) 20 grams maximum (microphone and preamplifier)

The final flight configuration represents a considerable advance in semiautomatic sphygmomanometers. It is small, lightweight and capable of operating in a noisy environment.

IMPLANT BIOTELEMETRY

Implant biotelemetry is recognized as one of the best means to obtain continuous internal physiological data without restraining the subject. Animal instrumentation for the Biosatellite program as well as a basic interest

in physiological phenomena has led NASA to investigate implant biotelemetry. Study of factors such as circadian rhythm requires continuous stable data acquisition over long periods of time. Advancing the state-of-the-art in this field assists in the general study of physiological responses to long flights and extraterrestrial environments.

Implant telemetry differs little from other telemetry systems. Biopotentials are picked up inside the body by sensors and amplified by a signal conditioner which modulates the transmitter. The transmitter radiates energy to an external receiver where the original signal is reconstructed and displayed. However, operation within an organism imposes novel requirements of sterility, physiological and psychological reactivity, size, stability, power level, and reliability.

NASA's activity in the field has resulted in several independent developments which have brought about a variety of solutions to the problems of implant biotelemetry. Development work has been done at the NASA Ames Research Center (refs. 4 through 11), the Space Sciences Laboratory, University of California, Berkeley (refs. 12 and 13), and the Department of Engineering, Case Institute of Technology (refs. 14, 15, and 16).

R. S. MacKay, while at the Space Sciences Laboratory, Berkeley, established some fundamental design criteria for implant biotelemetry. Requirements of small size and weight, high reliability, and low power drain have given impetus to the development of simple circuits in which the functions of sensor, signal conditioner, and transmitter are closely integrated. A circuit developed by MacKay (refs. 12 and 13) using this approach is illustrated in figure 18. Only one transistor is used in order to reduce power drain. The versatility of such a circuit is notable. Temperature can be measured by replacing the resistor R with a thermistor. Pressure can be measured by allowing pressure changes to move the core M. By attaching suitable electrodes across the input X–Y; other variables, among them pH, can also be recorded.

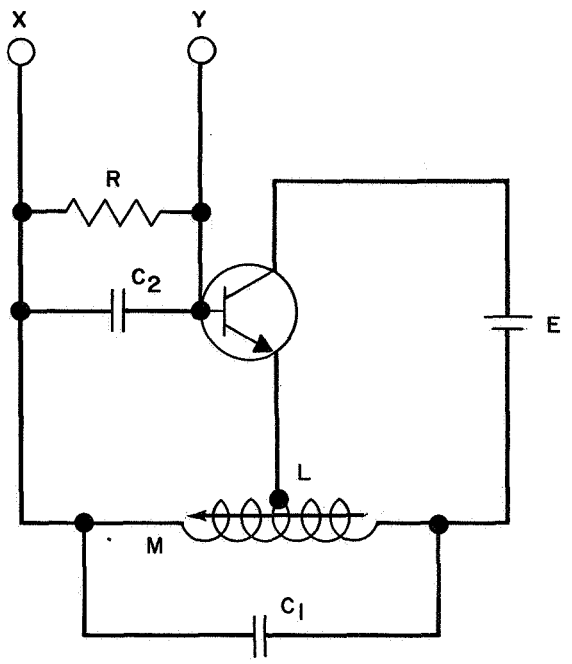

FIGURE 18.—Simple biotelemetry transmitter circuit developed at the Space Sciences Laboratory, University of California, Berkeley.

Such common biotelemetry circuits do not always meet rigorous performance specifications. Several fundamental limitations are:

(1) Variations in supply voltage introduce large errors

(2) Input impedance generally low

(3) Gain and frequency sensitive to temperature

(4) Range of frequency response and sensitivity inadequate

(5) Power consumption high.

T. B. Fryer and his colleagues at the NASA Ames Research Center have developed sophisticated circuits that circumvent the above limitations. By using advanced microelectronic circuit elements, such as high-quality silicon transistors, and by employing high-density packaging techniques, circuit sophistication was greatly increased without a corresponding increase in size.

An implantable microwatt transmitter (refs. 10 and 11) which accurately measures and telemeters deep body temperature for periods up to 2 years illustrates how electronic advances

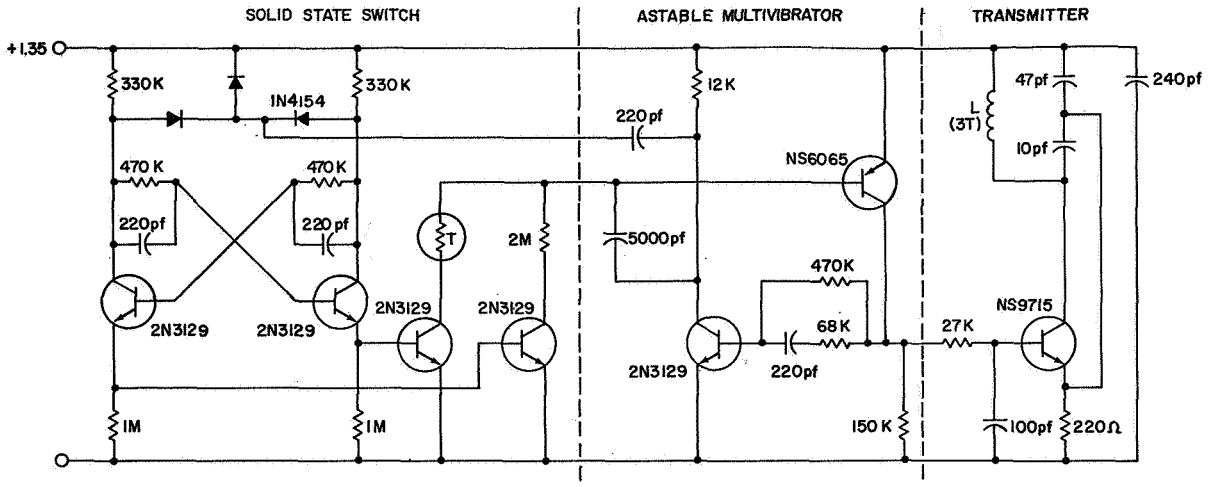

FIGURE 19.—Miniature biotelemetry transmitter developed at NASA/Ames for temperature measurement.

have been applied by NASA Ames Research Center to improve miniature implantable devices (fig. 19). The information transfer in this telemetry scheme is by means of pulse code modulation. The solid-state switch is a bistable multivibrator which periodically samples (chops) the continuous signal from the thermistor (T) in order to save power. The thermistor signal and precision resistor $R7$ control, in turn, the spaces between successive 15-microsecond pulses of the astable multivibrator. The interval between pulses varies from 8 to 20 milliseconds as the temperature being monitored varies from 45° to 35° C. The signal from the astable multivibrator activates the radio frequency (RF) oscillator.

Transistor $Q7$ functions as a frequency modulated RF oscillator, as well as a transmitter, while inductor L serves as a tuning coil, and as the transmitting antenna. Temperature information is available as the time period between RF pulses. Inherent compensatory provisions in this circuit, based on the relationship of the thermistor to the precision resistor-controlled pulse intervals, reduce the detrimental effects caused by battery voltage fluctuations, transistor drift, or other component instability. This insensitivity to extraneous forces is a significant feature, since it allows the use of miniature components with less critical specifications. Differential temperature measurements can be obtained by replacing the precision resistor $R7$ with another thermistor. The circuit can easily be modified for telemetering other physiological variables, such as pressure measurements (ref. 5), or biopotential measurements (ref. 6).

Figure 20 illustrates the internal construction details of a pressure telemetry implant developed at NASA/Ames. Figure 21 shows one method of miniature component assembly developed by NASA/Ames, in this case for a biopotential transmitter. There is a clear resemblance between this assembly technique and the "stacked cordwood" construction utilized in flight signal conditioner fabrication (see

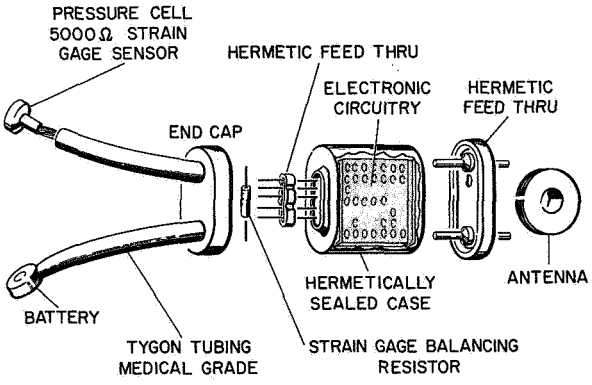

FIGURE 20.—Exploded view—NASA/Ames implantable pressure telemetry system.

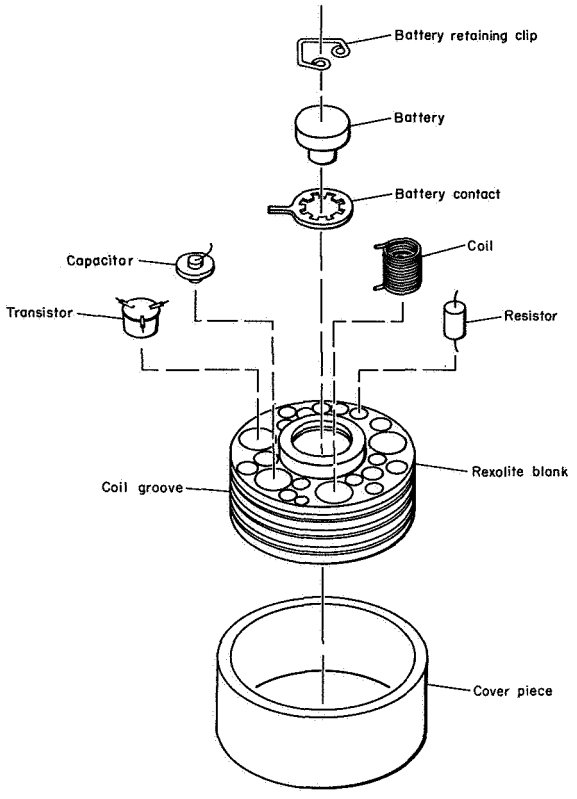

FIGURE 21.—Component assembly—NASA/Ames implantable biopotential transmitter.

chapter 8). When one remembers that the flight signal conditioners are approximately 100 times the size of the biotelemetry implants and yet perform for fewer functions, the design difficulties of the implant units become apparent.

W. H. Ko and his group at the Case Institute of Technology have specialized in biotelemetry circuits incorporating newer developments, such as tunnel diodes, backward diodes, and varacap diodes, as well as microelectronic techniques (refs. 14, 15, and 16). Two versions of biopotential transmitter circuits, utilizing tunnel diodes as the main active elements, are shown in figure 22. In Model *K*–1, the bias of the oscillator tunnel diode is varied to frequency modulate the carrier signal.

Model *K*–5 retains the sensitivity while further improving overall performance. In this configuration two other relatively recent solid-state electronic devices are introduced: the backward diode and the varacap diode. The backward diode serves a double purpose. First, it biases the tunnel diode oscillator into the region where frequency is insensitive to direct current variations caused by power supply changes. Secondly, it functions as a temperature-stable voltage regulator. The capacitance of the varacap diode varies with the input signal *S*, modulating the oscillator frequency. The input impedance of this circuit is raised to 100 megohms, compared with 1 megohm for Model *K*–1.

Multichannel implantable telemetry systems have been developed at NASA, Ames Research Center (ref. 17), as well as at Case Institute of Technology (ref. 16).

Power supply remains an outstanding problem for implant biotelemetry, and NASA programs have contributed toward its solution. Studies conducted at Ames examined the

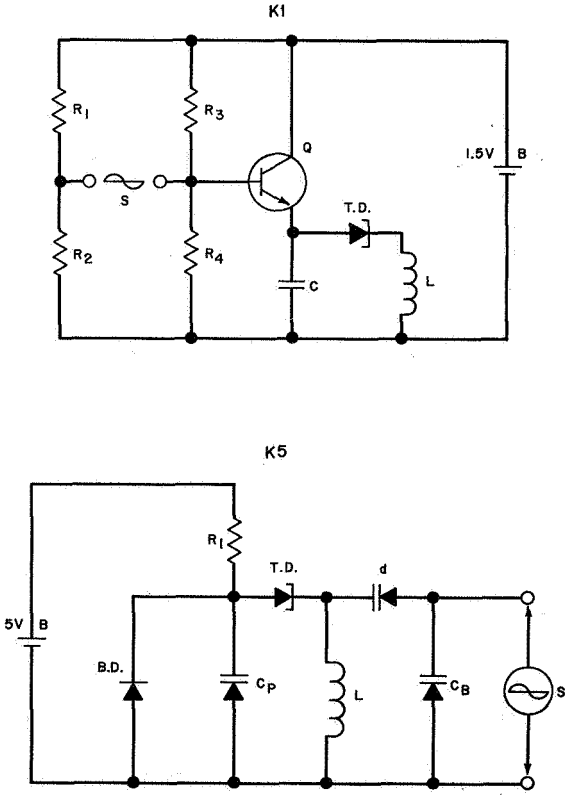

FIGURE 22.—Two single-channel biotelemetry transmitter circuits developed at Case Institute of Technology.

tradeoff between the short-life/long-range and long-life/short-range devices. Pulsed mode operation was one design approach. A pulsed bias allows the frequency-modulated transmitter to oscillate only when a subcarrier pulse is available for transmission, thereby reducing the power demand by the duty cycle of the subcarrier pulse. This revision was introduced in one of the Ames miniature biopotential telemetry systems. The pulsed mode operation increased battery life from 5 days to 4 weeks, and decreased the range from 100 to 10 feet, while leaving performance characteristics unaffected. Other ways of powering the implanted telemetry unit are under development. These include piezoelectric devices, the transmission of power through the skin by induction, and the use of body potential in various forms to supply the electronic device (ref. 18).

ADDITIONAL CONTRIBUTIONS

Three other signal conditioners are described briefly below.

(1) *Phonovibrocardiogram.* This unit was developed by Ling-Temco-Vought for in-flight recording of heart sounds (ref. 19). It features a broad frequency response, with much of its conditioning circuitry integral with the microphone sensor. It has already been applied to clinical research.

(2) *Impedance pneumograph.* A signal conditioner developed primarily for monitoring respiratory waveform during Gemini and Apollo flights. The circuit provides a wide acceptance range for input impedance changes without readjustment of parameters. It includes a unique peak detector section and other novel circuit approaches imposed by small package size (refs. 1 and 20). The general concept of this instrument is discussed further in chapter 7.

(3) *Vectorcardiograph.* Developed for the Apollo program, this combination of units permits in-flight recording of the vectorcardiograph by the Frank lead system. A Frank lead module accepts inputs from seven active electrodes and maintains signal phase and common mode rejection ratio adjustments, while providing an input/output impedance of 1 000 000 ohms (exceptionally high for this measurement). Three standard Apollo ECG spaceflight signal conditioners complete the system.

APPLICATION EVALUATION

Many of the NASA-originated and NASA-sponsored developments in signal conditioners are readily adaptable to other biological research areas. Ko and Slater (ref. 15) have stated:

> For future studies, researchers are calling for miniaturized electronic devices that can work inside the body; the demand is for smaller and smaller units that can gather more and more information. . . . They must be light, . . . they must have long life, impose a minimum restriction on the subject's movements, and create as little reaction as possible in the body's biological defenses against foreign matter. . . . Some of these problems are obvious to anybody who thinks about them; others require close cooperation between engineers and life scientists.

The biotelemetry devices being developed under NASA auspices are direct attempts to meet these stated needs and are certain to find application in future human and animal research work.[4] In addition, NASA-sponsored programs are helping to establish the ground rules of engineering/life sciences cooperation in laboratory research and, perhaps more important, in operational projects such as orbiting laboratories.

From an engineering systems standpoint, however, the signal conditioners that best characterize NASA's contribution are the small, rugged units used in spaceflight itself, such as the ECG and EEG amplifiers discussed above. In the main, these perform relatively simple functions. Their forte is high performance under adverse environmental conditions. They are very expensive compared

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[4] The clinical future of NASA biotelemetry was treated in the recent NASA Technology Utilization Report on space telemetry prepared by Hamilton Standard Division of United Aircraft Corporation (ref. 4). A NASA Technology Survey of blood pressure measurement (ref. 2) was published too early to include the Gemini unit discussed in this chapter.

to commercial units used for the same measurements. Although one might reasonably question their potential for nonaerospace application, it appears that these units, specialized as they seem, may well have significant influence on biomedical equipment and the bioinstrumentation system designer because spaceflight specifications are elevating clinical performance standards. Table 5 illustrates this point by comparing the major performance specifications of ECG signal conditioners for: (1) typical commercial units available before major spaceflight activity; (2) the Apollo unit, most recent of the NASA development line; (3) commercial standards recently recommended by the Subcommittee on Instrumentation, Committee on Electrocardiography, American Heart Association (AHA), ref. 21; and (4) a commercial unit currently available.

In such critical aspects as input impedance, common mode rejection, noise, and environmental operating range, the 1967 commercial ECG amplifier surpasses the AHA recommendation. The commercial model derived much of its circuit characteristics from the NASA Gemini and Apollo signal conditioners. At present, this amplifier represents outstanding medical instrumentation; but undoubtedly, other manufacturers will soon match it. Direct NASA influence at one source, then, will result in a general improvement of available instrumentation, and most likely, an upward revision of subsequent AHA recommendations. The same theme recurs throughout this report. Occasionally, specific NASA developments can be applied "as is" to similar, or even novel, nonaerospace work. But more frequently, the main effect of the NASA effort is to set in motion technological advances over a broad front.

TABLE 5.—*Signal Conditioner Performance*

Operating parameter	Pre-1960 commercial	1965 NASA Apollo	1967 AHA (ref. 21)	1967 commercial
Frequency response				
Direct writing (Hz)	0.5 to 100	0.2 to 100	0.05 to 100	0.2 to 100
Other recording (Hz)			0.05 to 2500	
Input impedance to ground (megohm)	0.5	44	0.5	10
Common mode rejection ratio (db)	60	over 100	60	over 100
Noise referred to input (RMS μV)	10	2	10	2
Environmental				
Temperature (°C)	----	−20 to 70	10 to 50	0 to 55
Pressure (psi)	----	14.7 to 1.0	14.7 to 10	14.7 to 7
Relative humidity (1%)	----	0 to 100	5 to 95	0 to 100

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CHAPTER 5

Spaceflight Medical Monitoring

NASA is engaged in a far-reaching effort to accumulate biomedical information regarding man's ability to function in space. During manned flight, immediate biomedical data from the astronauts are combined with previously gathered information by a medical monitoring team operating at Manned Spacecraft Center in Houston. While the flight is in progress, the team must continually ascertain the immediate medical state of the astronauts; and, on the basis of incoming and historical data, determine their ability to continue the flight and reenter the earth's atmosphere safely. After the mission ends, the team must use the newly acquired data in planning subsequent flights.

This chapter describes the techniques adapted by NASA in the Gemini and Apollo programs to bring the required biomedical information to the medical monitoring team. NASA has termed its functional combination of techniques a "bioenvironmental information system" (BIS). As was pointed out in chapter 2, biomedical information requirements have changed during the course of the space program as missions have lengthened and mission objectives have become more varied. NASA's bioenvironmental information system has necessarily changed along with the space missions. In particular, the transition from the Gemini program to the operationally more complex Apollo program has resulted in extensive revision of monitoring equipment and monitoring philosophy. Some of the design rationale underlying the transition is presented to illustrate NASA's approach to this important bioinstrumentation problem.

SPACEFLIGHT DATA TRANSMISSION

For the Gemini flights, medical decisions emanated from the medical monitoring team at the Houston Mission Control Center (MCC). These decisions were based on telemetered data originating from the spacecraft bioinstrumentation system and reaching Houston via several telemetry links (ref. 1). Figure 23 shows the general flow of data from the

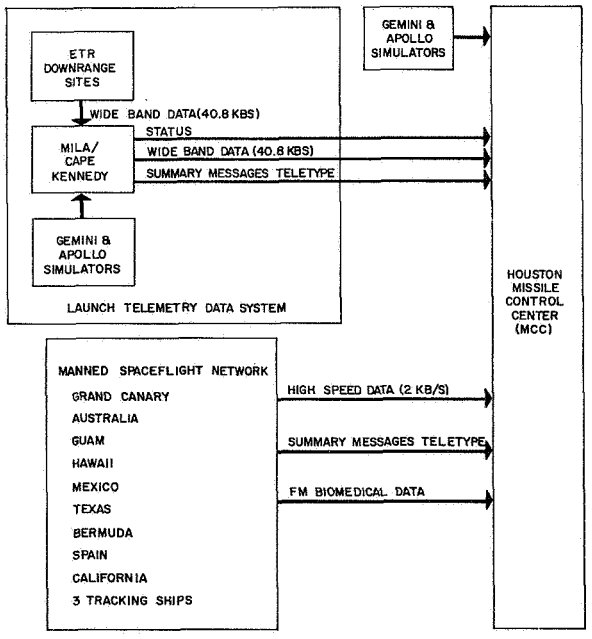

FIGURE 23.—Gemini/Apollo data transmission system.

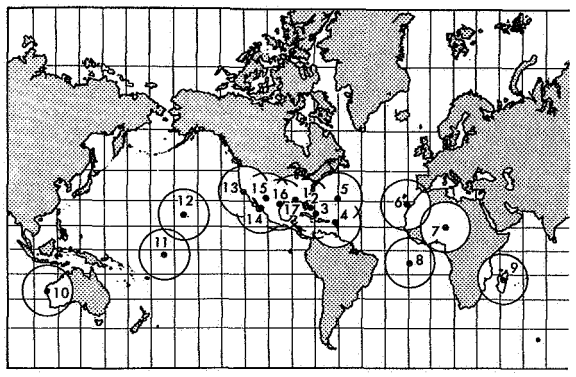

FIGURE 24.—Tracking stations—Gemini/Apollo Manned Spaceflight Network.

spacecraft to the medical monitor's console at the MCC. Before launch, data came directly from the launch complex at Cape Kennedy. After launch, the Cape Kennedy complex became part of the worldwide Manned Space Flight Network (MSFN). The MSFN consists of a number of tracking stations geographically distributed, as shown in figure 24, to track and maintain radio contact with the spacecraft throughout its flight. The number of stations actually able to acquire the spacecraft, however, varies with the specific orbit; and the time that the station is in contact with the capsule also varies.

Several of the ground tracking stations—Hawaii, Texas, Cape Kennedy, Grand Bahama, Grand Turk, and Antigua—are connected with the MCC through high-speed data lines. These stations relay the biomedical telemetry virtually unchanged to Houston. The other tracking stations have only low-speed teletype and voice links to the MCC. At some of these stations, particularly on board ship, the biomedical data are reduced on site, and summary messages are sent on to Houston where they are intercepted by the medical monitor for display and evaluation. The incoming data are taperecorded at the remote sites, however, so that if the teletyped summary indicates an anomalous situation, the original data can be scanned for the source of trouble.

GEMINI MEDICAL MONITORING

Gemini medical monitoring depended heavily upon examination of the raw safety data as they were received from the orbiting spacecraft (see table 3). Each time the spacecraft was acquired by a ground station, two ECG signals and the respiration waveform signal for both astronauts were routed to the central medical monitor's station for recording and analysis. At specified intervals during the day, the MCC monitor also received blood pressure signals, consisting of Korotkow sounds superimposed on an arm cuff pressure decay curve. These signals were recorded on a direct-writing recorder as they were received; figure 25 presents a typical portion of Gemini biomedical data. Oral temperature readings taken in flight were transmitted periodically by voice communication.

Although the Gemini medical monitors had available cardiotachometers and respiration tachometers for meter displays of rate information from the ECG and impedance pneumograph signals, they preferred to derive these values by hand measurement of the strip chart records, using plastic scales or reference marks on the recorder platen. In some ways, this provided greater flexibility of observation. For example, during a portion of the Gemini VII flight, astronaut Borman's respiration channel malfunctioned and respiration rate was determined by the heart axis deviation observable on the sternal ECG. On the whole, however, the procedure reflected a lack of confidence in the tachometry circuits and associated analog meters.

The rates recorded by measurement at Houston were logged by the medical monitor at his console and transmitted by telephone to the flight surgeon in the main Mission Control Room. The same type of heart rate and respiration rate measurements were made by medical monitors at the remote tracking sites. In their teletyped messages to the MCC, they reported:

(1) Heart rate (mean, minimum, and modal value)

(2) Respiration rate

(3) Medical comments (such as ECG normal)

(4) Other related information (cabin CO_2

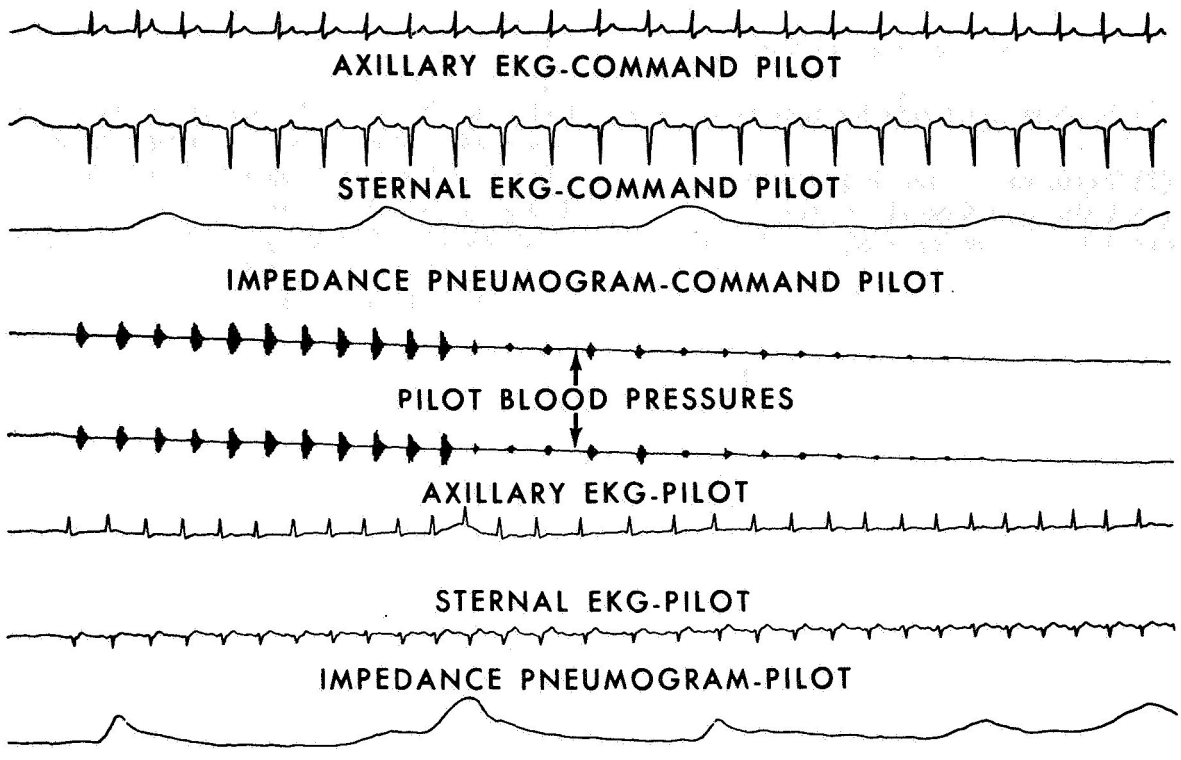

FIGURE 25.—Sample of Gemini biomedical data.

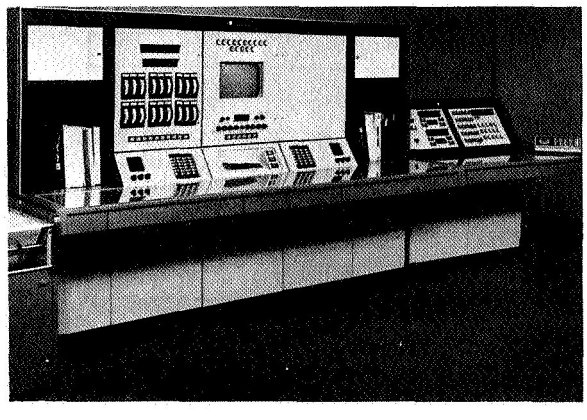

FIGURE 26.—Gemini remote site aeromedical monitoring console.

reading, status of the biomedical tape recorder, malfunctioning channels, etc.)

The teletyped summary messages were posted as they arrived at Houston and arranged so that the last few messages could be seen on the MCC closed circuit TV system. Figure 26 illustrates the Aeromedical Monitor's Console installed at the remote stations.[1] The console provided for analog waveform display through oscilloscope and strip chart recorder and for a meter display of heart rate information.

Along with the abbreviated rate summaries, a more complete analysis of the ECG waveform and blood pressure data obtained on a telemetry acquisition was performed by the medical monitoring team at MCC. Figure 27 presents the NASA log sheet for this information, which was also obtained by hand measurement of the strip chart recordings. Twice a day, the following data were also summarized for each crew member:

(1) Oral temperature
(2) Heart rate

[1] These consoles were developed for the Gemini program by Bendix Pacific Division, North Hollywood, Calif.

(3) Respiration rate
(4) Blood pressure—pre-exercise
(5) Blood pressure—post-exercise
(6) Highest heart rate for that period (12 hours)
(7) Food, water, and sleep report
(8) Urine and feces elimination

Heart rate, respiration rate, and blood pressure were plotted against Gemini Elapsed Time (GET), and displayed to the flight surgeon on demand through the closed circuit TV system.

In addition, the medical monitoring team had available several data summary charts generated by the main computing equipment, which could be viewed on specific TV channels. These charts consisted of:

(1) *Gemini (GEM) physiological temperatures.* A plot of command pilot suit temperature, pilot suit temperature, and cabin air tem-

ELECTROCARDIOGRAPHIC LOG

MISSION_____ SITE _____ REV._____ DATE_____

AOS LOS (GET)

	COMMAND PILOT			PILOT		
MEASUREMENT	AOS +30s.	MIDDLE OF PASS	LOS −30s.	AOS +30s.	MIDDLE OF PASS	LOS−30s.
MEAN HR (30 SEC.)						
MAX HR						
VARIATION						
RR INTERVAL						
PR INTERVAL						
QRS INTERVAL						
QR (VAT) INT.						
QT INT. (UNC.)						
QT INT. (COR.)						
$QT_{unc.}/TQ$ RATIO						
MIN HR						
VARIATION						
RR INTERVAL						
PR INTERVAL						
QRS INTERVAL						
QR(VAT) INT.						
QT INT.(UNC.)						
QT INT.(COR.)						
$QT_{unc.}/TQ$ RATIO						

BLOOD PRESSURE

GET: COMMAND PILOT

MEASUREMENT	PRE-EX.	POST-EX.
SYSTOLE/DIASTOLE		
PULSE PRESSURE		
HEART RATE		
PP X HR		
Q-K INTERVAL		

GET: PILOT

MEASUREMENT	PRE-EX.	POST-EX.
SYSTOLE/DIASTOLE		
PULSE PRESSURE		
HEART RATE		
PP X HR		
Q-K INTERVAL		

FIGURE 27.—Gemini electrocardiographic log format.

perature versus GET, generally for several hours.

(2) *GEM physiological meters.* A chart presenting various temperatures and pressures relating to the environment and suit at a specific time, as well as oral temperature (when available).

(3) *GEM physiological summary tab.* A chart summarizing *available* physiological data and certain cabin environmental data for the last three data acquisitions of the spacecraft.

(4) *GEM physiological summary history recall.* Similar to Chart III, except that flight history 12 hours old was presented.

(5) *GEM physiological summary history.* Similar to Chart III; six previous passes plotted.

Although these charts theoretically provided for physiological data summary, no physiological information appeared on them, because no provision was made in the main computer system for handling these data. The main use of the charts to the medical monitor, then, was in roughly comparing the manually derived data with posted environmental variations in the spacecraft.

Several computer processing routines were applied to short samples of the flight safety data on an experimental basis during the later Gemini missions. A computer program was written to derive the following heart rate information from the raw ECG signals, using analog tapes generated at Mission Control as input: (1) mean, (2) standard deviation, (3) variance, (4) maximum, and (5) minimum. A second experimental arrangement utilized computer analysis of ECG waveforms to produce a clinical diagnosis during the space missions.

For postflight data analysis, analog tape in standard format was produced by a series of conversions of the specialized tape from the in-flight recorder. Respiration rate and heart rate information was generated from the final tape by playing it back through a cardiotachometer and respiration tachometer to produce a tape that had two zero crossings per beat or breath. This tape (including a time code) was then fed to an analog-to-digital converter to derive a digital tape for use with a computer. The computer was programmed to derive heart rate and respiration rate recorded and to develop plots of heart rate and respiration rate versus time.

APOLLO MEDICAL MONITORING

In preparation for the Apollo program, NASA has markedly updated the BIS, particularly the biomedical data displays, and the medical monitors' control over the incoming data (refs. 3, 4, and 5). Figure 28 presents the data flow paths in the new system installed at MCC.[2]

The biomedical preprocessors are designed to handle ECG and impedance pneumograph (ZPN) signals from several astronauts simultaneously on single or dual missions (i.e., one to three astronauts simultaneously from each of two spacecraft). There are two cardiotachometers, two respiratory rate units, and an ECG waveform analyzer. A 30-second FM tape loop recorder receives the same signals as the biomedical preprocessors and provides a 30-second delay of selected real time signals. The delayed signals are displayed on strip chart recorders upon request.

Each of the cardiotachometer and respiratory rate preprocessors digitizes a selected ECG or ZPN analog signal. The outputs provide digital signals representing instantaneous and average rates, computed over 6, 10, 15, or 30 seconds. In addition, each tachometer preprocessor provides an analog heart rate and respiration rate signal for display on the strip chart recorder. The input to the ECG waveform analyzer is a selected ECG signal from the patch board; the output is a digital representation of the ECG complex.

Digital outputs of the preprocessors enter a Univac 494 computer which prepares the data to be fed to the larger IBM/360 (part of the Real Time Computer Complex). The Univac 494 tags the incoming raw data with GMT words, astronaut identification, and activity

[2] This system and the subsequently described Aeromedical Console were developed and installed by Philco Corp., Houston.

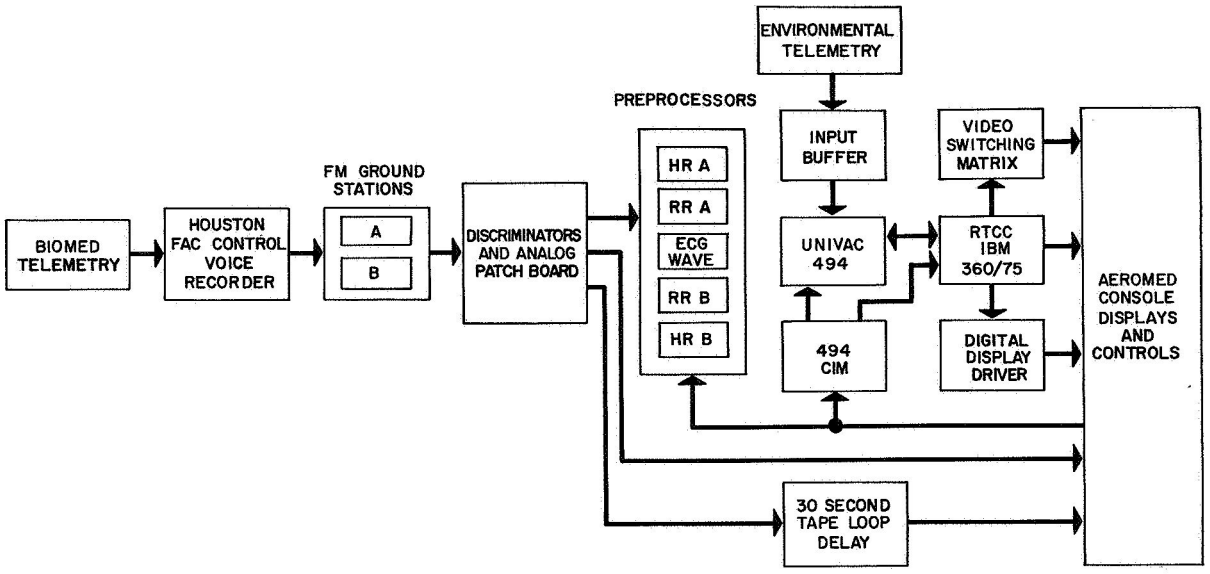

FIGURE 28.—Bioenvironmental data system, NASA Mission Control Center, Houston.

mode tags supplied from the aeromedical console through the interfacing CIM computer. The IBM/360 processes the real-time rate data as they are received from the Univac 494. It checks the data for abnormalities by comparing the actual rate levels with acceptance ranges stored before or during the mission. Should an abnormality occur, the IBM/360 sets an alarm on the aeromedical console through the digital display driver, which simultaneously assigns a digitized event code to the abnormality.

The IBM/360 also manipulates the input data and generates real-time data summaries of heart and respiration rates. These summaries are displayed on a scope face at the console through the video transmission matrix, which switches to any one of two sets of data on a dual mission. The summaries present the mean, maximum, minimum, standard deviation, and variance of heart and respiration rates. This information is also stored in the computer, to be available "on-call" for mid- and postpass summaries and for subsequent automatic retrieval.

The aeromedical console pictured in figure 29 is the operations center of medical monitoring activity. One unit is in the Staff Support

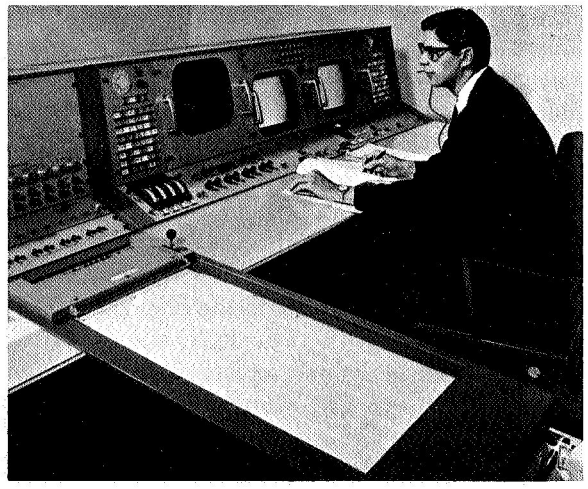

FIGURE 29.—Aeromedical console, NASA Mission Control Center, Houston.

Room (SSR); its information display capabilities are shown schematically in figure 30. These displays provide the monitoring surgeons with:

(1) TV and cathode ray oscilloscope (CRO) displays:

a. Digital readout of continuously updated instantaneous heart rate, average heart rate, and average respiration rate

SURGEONS AEROMEDICAL CONSOLE. A SIMILAR CONSOLE IN THE MISSION OPERATIONS CONTROL ROOM (MOCR) INCLUDES ALL SSR DISPLAYS EXCEPT THE STRIP CHART RECORDER.

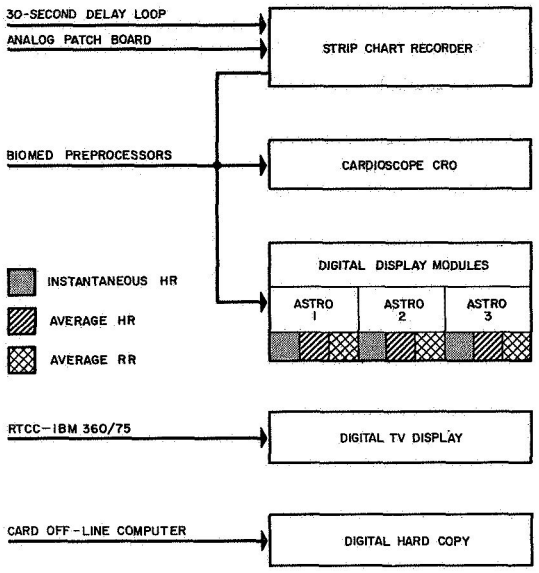

FIGURE 30.—Display modules of the MCC aeromedical console.

b. Digital display of environmental parameters

c. ECG waveform overlay (real time and playback)

d. Data summaries for specific past intervals, as well as playback display and raw data shown for the previous 6 data hours. This information is obtained on demand from tape memory.

(2) Strip chart recordings:

a. Incoming signals, raw or preprocessed rates, at monitor's request.

b. Abnormal signals immediately as limit crossings are recognized by computer

c. Incoming signals from 30 seconds previous

(3) Printed postpass summaries:

a. Pass identification (site, date, time, length)

b. Identification of crew member samples

c. Astronaut activity summary

d. Heart rate summary (mean, standard deviation variance, maximum, minimum)

(4) Teletype hardcopy:

Computer-printed summaries, reviewed by the medical staff before transmittal to the remote monitoring sites

(5) Alarms:

a. Single alarm indicator illuminated upon limit crossing

b. Multiple alarm indicator signaling second alarm occurring before reset

A similar console in the Mission Operations Control Room (MOCR) includes all SSR displays except the strip chart recorder. By means of the console controls, the medical monitor selects available information for display, specifies particular operations on stored data, and reenters observations into computer memory. Table 6 summarizes the major controls and their function, illustrating the operating potential of the aeromedical console.

BIOENVIRONMENTAL INFORMATION SYSTEM: DESIGN EVOLUTION

The Bioenvironmental Information System (BIS) employed during the Mercury and Gemini missions reflected a "clinical" monitoring strategy—in essence, a qualitative approach based on medical experience and rule-of-thumb analysis. Biomedical data were presented to the medical monitors largely in raw analog form. The medical monitors were engaged primarily in visual inspection of analog displays (cardioscopes, strip charts, and meters) and manual reduction of incoming data. The medical monitor's assignment included many routine mechanical operations. Lack of automated data recall made it difficult to compare real-time flight data from previous missions and with ground-based data. Most of the complicated data reduction and data analysis was carried out postflight, using information from the strip chart records and the tape recovered from the onboard flight recorder. Thus, for the most part, the medical decision process was carried out on an "open loop" basis, without significant feedback. Successful monitoring depended heavily on the professional competence and the continuous presence of the medical staff.

TABLE 6.—*Major Control Operations of MCC Apollo Aeromedical Console*

Console unit	Control	Function
TV monitor	Mode	Selects (1) RTCC (any data from the IBM/360 Computer), or (2) biomed real-time or summary data.
Cardioscope	Mode	Selects (1) normal display of real time or playback ECG waveform, or (2) overlay display of successive complexes.
Computer	Mode	Selects (1) playback of any raw data from previous 6 hours, or (2) summary printout or display of data for selected time period.
	Teletype	Computer printout of data summary teletyped to remote sites after approval by medical officer.
	Limits	Establishes upper and lower limits on selected variables.
Identification	Astronaut	One of three astronauts is manually identified by pushbutton.
	Activity	Astronaut activity is classified by pushbutton into (1) Normal, (2) Sleep, (3) EVA, (4) Exercise, (5) Suited, (6) Unsuited.
ECG input	Select	One of four monitoring conditions is selected: (1) axillary, (2) sternal, (3) EVA, (4) lunar module.

With the completion of the Gemini program, the focus of medical monitoring shifted from immediate safety to long-term operational and experimental aspects. It has become necessary to provide the medical monitoring team with information describing the crew's potential to survive and operate in space for an extended period of time, as well as with information concerning their immediate medical status. The updated BIS design reflects NASA's transition from the clinical to the operational approach. The new system is more automated; it offers a greater amount of descriptive information and better feedback capabilities for decision making.

Automation is introduced at several stages in the new system. Incoming data are immediately digitized by analog-to-digital conversion units. The digitized data are buffered, processed, and manipulated by a high-speed computer. Consequently, descriptive parameters can be displayed in digital format; and a variety of computer-generated summaries and plots are made available to the medical staff. Data compression is accomplished on successive levels: instantaneous displays, daily summaries, flight summaries (a collection of the daily summaries), and postflight analyses. Tabular summaries and plots of any combination of dependent variables help the monitoring team recognize trends in physiological response. The system offers both automatic and manual data retrieval capability. Storage of physiological limits for various stress conditions in the computer permits the installation of automatic alarms. System efficiency is also

enhanced by display facilities that correlate biomedical and environmental parameters. In combination, these features increase feedback and at the same time remove a great deal of the routine workload so that the medical monitoring team can devote more time to decision making.

NASA planning personnel (refs. 6 and 7) expect BIS to continue to evolve. The current objective is to reduce and analyze as much raw data as possible in real and near-real time, and to close gradually the gaps between data acquisition, data interpretation, and research. As the capabilities for realtime analysis increase, the system will assume a more descriptive and inferential nature. The inferential characteristic will be added by applying appropriate statistical tools. Realtime waveform analysis will further strengthen the descriptive function, and mathematical models of physiological processes will supplement statistical analysis (ref. 8). The combination of the two will add a predictive capability to the system; and, as more basic space data are acquired, may lead eventually to some automation of the medical decision process. (In the updated BIS, automation goes only as far as supplying information in an appropriate format to the medical monitors, the decision makers.) Finally, it is expected that the application of modern communication and information theory concepts to the biomedical signals will permit substantially more onboard data compression, offsetting the limitations of downlink channel capacity (ref. 9).

APPLICATION EVALUATION

Comprehensive and continuous patient monitoring currently represents one of the most rapidly growing facets of clinical medicine. Although real-time monitoring is initiated for a variety of reasons, including research data acquisition and diagnosis, intensive patient care is perhaps the activity most amenable to the influence of NASA technical contributions. Within the last few years, many hospitals have initiated intensive care procedures as a means of preventing the deaths of their patients. These procedures generally share the following characteristics:

(1) Assembly of all critically ill patients in an easily supervised, compact area, generally called the intensive care unit (ICU). The ICU may consist of the postanesthesia recovery room, the postoperative recovery room, the cardiac care unit, or some combination of these.

(2) Round-the-clock individual care by nurses specially trained in handling emergencies and sometimes especially selected to handle responsibilities approaching those of the attending physician.

(3) Use of some type of semiautomatic monitoring equipment attached to each patient to warn the nurse and other cognizant personnel of serious changes in his condition.

Generally, the monitoring equipment will inform the nurse of an emergency (for example, cardiac arrhythmia) and the nurse will call in physicians and nearby specialized apparatus, while starting emergency aid procedures. Within a few seconds, a skilled team can be assembled to cope with the medical problem. Recent efforts in the field of shock monitoring have made use of small and medium sized computers as elements in the linkage between patient and medical monitor (refs. 10 and 11).

The main purpose is to utilize fully the few minutes in which death can still be averted. Intensive care thus involves a unique symbiosis of men and machines; it consists of long periods of passive monitoring interspersed with brief bursts of swift activity. There is no doubt that this technique can save lives. It is, however, quite expensive and is demanding of personnel.

When adaptation of a desirable innovation is hampered by its cost and when much of that cost arises from skilled labor, technology may have something to offer toward a solution to that problem. The production of consumer goods exemplifies this point. Of course, the problems associated with intensive patient care are not the same as those of assembly lines, but if the skills of the nurses and physicians can be employed better by the judicious use of equipment and technique, many more lives

might be saved than are now, with little more expenditure.

There are many reasons why space monitoring techniques would be beneficial to hospital applications, but perhaps the most outstanding is the application of space technology's *systems philosophy* from the start. As Meltzer, Pinneo, and Kitchell point out, "The concept of intensive coronary care as a *system* is fundamental to the entire success of this program" (ref. 12). Although some hospitals have utilized systems concepts in planning (ref. 13), much of the instrumentation previously produced for hospital monitoring has not reflected a systems design approach. Equipment design and installation have often been ad hoc, neglecting such factors as basic information requirements, unit interfacing, demands on operating personnel, and operating room or bedside clutter. NASA spaceflight monitoring experience provides valuable examples of largescale system development. More important, perhaps, the evolution in NASA systems design, spurred by changing space monitoring needs, presents the designer of patient monitoring systems with some guidelines that may aid him.

It is frequently necessary, however, for the medical designer to modify some aspect of NASA system implementation, while maintaining the same basic principles. For example, at the Manned Spacecraft Center, real-time biomedical data processing represents a subtask of the large central computer. This is an excellent approach when such a facility with the requisite spare capacity is available. Hospitals may not yet have large computer installations or the existing computer may be completely occupied by other tasks. In such cases, there are still ways to obtain the benefits of computer-aided monitoring by using the new class of small computers, discussed further at the end of chapter 6. Similar considerations apply to the NASA techniques of data acquisition and special display generation.

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CHAPTER 6

Advances in Biomedical Data Processing and Analysis

This chapter describes several advanced techniques developed under NASA sponsorship for the processing and analysis of biomedical data. The objective has been to narrow the gap between data processing and data analysis, which from the technical point of view are inherently related, inasmuch as the means by which biomedical data are analyzed depends to a large extent on the processing scheme. From an operational standpoint, merging the two procedures permits faster data interpretation, which is valuable equally in space and at critical ground installations.

The contributions presented here illustrate the merger process in different ways. The time-line approach links descriptive statistics to slices of raw data. "Yes/no" reduction provides a simple descriptive framework for continuous data. Both the time-line approach and the "yes/no" method yield processed data ready for immediate computer input and further analysis. The EEG contour map serves as an effective data compression tool and, at the same time, offers an immediate means of analysis and interpretation by visual inspection. This is also true of such mathematical processing techniques as waveform averaging and signal autocorrelation.

Sophisticated hardware and mathematical techniques lie at the core of most of these data processing methods. NASA has learned that application of these tools requires careful judgment at each stage of the processing chain. For example, extremely coarse analog-to-digital conversion of prime data may result in losses of information which cannot be restored by even the most sophisticated computer techniques. On the other hand, using higher sampling rates than necessary increases the cost and the time needed for analog data processing. Again, "clean" biomedical signals can be obtained by operations such as filtering and averaging. These operations are effective in reducing noise, improving the signal-to-noise power ratio and delivering a "smoother" waveform. However, in these processes, relevant information may also be averaged, filtered, or integrated out. Along these lines, Jasper has stated that one of the problems in the use of computers in the work on the brain is the loss of information in averaging data (ref. 1).

In planning data processing, then, one must take full account of the nature of the primary data. Mathematical methods of analysis must be carefully evaluated and adopted in accordance with both the signal structure and the overall medical objectives. The NASA examples discussed here are results of such examinations. Satisfactory results were obtained only after optimal values were found for the various parameters involved, such as sampling rate, number of samples to be averaged, period of integration, bandwidth, and others. Equivalent examinations would be needed in terrestrial medicine.

TIME LINE MEDICAL DATA

In the space program, medical data are acquired almost continuously during spaceflight and ground simulation. These data have to be prepared for effective in-flight and postflight

scrutiny and analysis. During a mission, the main objective is to have the data in proper form for comparison with data from other missions or other phases of the same mission. The postflight objective is to have the data available in a computer-compatible form for further research and analysis. Both objectives require the data to be arranged in a standard, interchangeable format. A method termed the "Time Line Approach to Data Tabulation and Compression" was developed at NASA to satisfy these requirements (ref. 2).

The time line method is a hierarchical structure. Its basic element is the single data sheet that contains all relevant biomedical information for a given time interval of a space mission or a space simulation run. During stressful periods, such as exit and reentry, when variables change rapidly, the time interval chosen is shorter than under less stressful conditions. The next level of the hierarchy is a matrix of single data sheets; the last level is a matrix in which the entries are sets of data sheets. The medical data from the Mercury and Gemini flights were prepared in time line format. Figures 31, 32, and 33 represent samples from that data accumulation.

Figure 31 illustrates a 10-second interval data sheet and the analog record from which the tabular data were derived. The tabulated data contain information concerning the astronaut's physiological state and performance, as well as the spacecraft environment. In addition to the digitized raw data, descriptive statistical parameters such as mean, standard deviation (sigma), variance, and standard scores, are included. The data sheet heading specifies the mission (Mercury Atlas MA–9) and the mission elasped time to which the data on the sheet pertain (20 to 30 seconds after lift-off). The astronaut's activity during the 10-second interval is recorded under the heading of "communications." During this particular interval, the astronaut started the backup clock. Activities are digitally coded in terms of criticalness, difficulty, duty, and procedure for computer storage. The individual data sheets were transferred to magnetic tape, and stored for subsequent analysis.

TIME-LINE DATA

PROJECT MERCURY
MERCURY ATLAS NO.

MISSION ELAPSED TIME = 00,00,20 TO 00,00,30
DATE

HEART RATE BEATS/MIN	STANDARD SCORE	RESPIRATION RATE BREATHS/MIN	STANDARD SCORE	ACCEL. Z-AXIS G-S	STANDARD SCORE	SUIT-IN TEMP DEG F	SUIT-OUT TEMP DEG F	CO2 PARTIAL PRESSURE PSIA	CABIN PRESSURE PSIA
115.60	38.20	16.90	36.40	1.77	50.30	65.22	84.52	.0000	15.245
112.14	36.79	15.78	35.39	1.90	50.96	65.18	84.46	.0000	15.213
112.14	36.79	22.72	41.63	1.77	50.30	65.22	84.52	.0000	15.198
113.85	37.49			1.71	50.00	65.26	84.58	.0000	15.229
115.58	38.19			1.71	50.00			.0000	15.229
115.60	38.20	"		1.64	49.65	"	"	.0000	15.245
113.85	37.49			1.37	48.28			.0000	15.276
115.60	38.20	"		1.90	50.96	"	"	.0000	15.198
112.14	36.79			2.43	53.65			.0000	15.198
113.85	37.49	"		2.04	51.67			.0000	15.198
113.85	37.49			1.71	50.00	"	"	.0000	15.174
115.58	38.19			1.90	50.96			.0000	15.158
119.28	39.69						****		****
121.18	40.46	"		"		"	MEAN	"	MEAN
121.18	40.46								
123.20	41.28			"		65.22	84.52	.0000	15.216
121.18	40.46	"							
119.26	39.68			"					
123.17	41.27	"							
123.20	41.28								
"		"		"					
******	******	******	******	******	******				
MEAN =	117.07	MEAN =	18.46	MEAN =	1.82				
SIGMA=	3.96	SIGMA=	3.72	SIGMA=	.25				
VARIANCE=	15.68	VARIANCE=	13.88	VARIANCE=	.06				

ACTIVITY

1. PLANNED	START BACKUP CLOCK.
2. INDICATED	START BACKUP CLOCK.

COMMUNICATIONS

00,00,20	CC	MARK.
00,00,23	P	ROGER. AND THE BACKUP CLOCK IS RUNNING
00,00,25	CC	ROGER. YOU LOOK GOOD HERE, GORDO.
00,00,27	P	ROGER. FEELS GOOD, BUDDY.
00,00,29	CC	GOOD SPORT.

FIGURE 31.—Time-line data sheet for a 10-second interval of a Mercury flight.

	T-60 TO T-59	T-59 TO T-58	T-58 TO T-57	T-57 TO T-56	T-56 TO T-55	T-55 TO T-54	T-54 TO T-53	T-53 TO T-52	T-52 TO T-51	T-51 TO T-50	T-50 TO T-49	T-49 TO T-48	T-48 TO T-47	T-47 TO T-46	T-46 TO T-45
1st SUBORBITAL (MR 3)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2nd SUBORBITAL (MR 4)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1st ORBITAL (MA 6)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2nd ORBITAL (MA 7)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
3rd ORBITAL (MA 8)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
4th ORBITAL (MA 9)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1st GEMINI (GT 3)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2nd GEMINI	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

X = ONE DATA SHEET

FIGURE 32.—Summary of available data sheets for sequential time intervals, Mercury and Gemini flights.

Figure 32 presents a fine summary of available data sheets for several space missions. Each row of this matrix contains the medical data over a period from launch minus 60 minutes to launch minus 15 minutes for a single mission. Each matrix column contains data of like time periods for different missions. The consecutive data sheets available in a row yield the continuous data for a particular mission phase, while the vertical sheets comprise the medical information from similar epochs of different missions.

Figure 33 illustrates a coarse summary of a similar group of missions. It represents a breakdown of the spaceflight mission by specific periods during which data were collected and organized in time line format. It covers the Mercury program, indicating what data tabs (tabular summaries) are available per flight, what periods can be compared among flights, and, for the comparison periods, how fine are the tabulated data samples. The matrices are ideal analytic tools for the medical monitors.

YES/NO DATA REDUCTION

Thousands of feet of strip chart and magnetic tape records are collected during prolonged aerospace missions. Analyzing the data manually is time consuming and requires highly qualified personnel for coding and interpretation. "Yes/no" data reduction is one of several methods developed to cope with large amounts of biomedical information. Described by Sem-Yacobson et al., it has been applied to flight data acquired at the NASA Flight Research Center (ref. 3).

The technique is based on reduction criteria that determine what information in the primary signal should be retained after the reduction process. The criteria themselves are determined by the investigator's objectives. Criteria may relate to signal amplitude, period, slope, or any combination of these parameters. The method is termed "yes/no" because it yields only binary information concerning the signal parameters; i.e., the resultant output contains no numerical values but indicates only if the limits of each criterion are exceeded ("yes") or not ("no") as a function of time. The amount of signal information retained after reduction depends on the number of criteria chosen.

Figure 34 is an example of twofold "yes/no" reduction—amplitude and duration—applied to a representative waveform. The left column of figure 34 shows the sequence of operations performed on the primary signal to detect whether the signal exceeds the duration threshold, while the right column describes the equivalent for the amplitude threshold. The primary signal in A is rectified to produce the trace in B. The trace in C is a dc voltage that starts when the primary signal goes from a negative to a positive value and is reset to zero when the primary signal goes from a positive to a negative value. The pulses in D are triggered by a one-shot generator when the primary signal changes from a negative to a positive value.

The voltage in E increases at a constant rate, starting from zero at the instant specified by the first pulse in D, and is reset to zero at the instant marked by the second pulse in D. This voltage translates the time duration of the period of the primary signal into a voltage amplitude. The period threshold of the criteria, marked by the dotted line in E, is compared with this voltage. If the lines intersect,

	MR-3	MR-4	MA-6	MA-7	MA-8	MA-9	MA-9	TOTAL
15 MIN PERIOD (1 MIN SAMPLES AT A COMMON TIME BETWEEN T-60 MIN AND T-2 MIN)	15 MIN DATA CONTINUOUS 15 TABS	15 MIN DATA CONTINUOUS 15 TABS	15 MIN DATA CONTINUOUS 15 TABS	15 MIN DATA CONTINUOUS 15 TABS	15 MIN DATA CONTINUOUS 15 TABS	15 MIN DATA CONTINUOUS 15 TABS		90 TABS
T-2 MIN TO LIFT-OFF (10 SEC SAMPLES)	2 MIN DATA 12 TABS	2 MIN DATA 12 TABS	2 MIN DATA 12 TABS	2 MIN DATA 12 TABS	2 MIN DATA 12 TABS	2 MIN DATA 12 TABS		72 TABS
LIFT-OFF TO ZERO G (10 SEC SAMPLES)	2 MIN 40 SEC DATA 16 TABS	2 MIN 40 SEC DATA 16 TABS	5 MIN DATA 30 TABS	5 MIN DATA 30 TABS	5 MIN DATA 30 TABS	5 MIN DATA 30 TABS		152 TABS
ZERO G TO -15 MIN (1 MIN SAMPLES)	ONLY 5 MIN OF DATA 5 TABS	ONLY 5 MIN OF DATA 5 TABS	15 MIN DATA 15 TABS	15 MIN DATA 15 TABS	15 MIN DATA 15 TABS	15 MIN DATA 15 TABS		70 TABS
ZERO G -30 MIN TO ZERO G -45 MIN			15 MIN DATA 15 TABS	15 MIN DATA 15 TABS	15 MIN DATA 15 TABS	15 MIN DATA 15 TABS		60 TABS
PERIOD OF ASTRONAUT ACTIVITY			00:25:00 TO 00:30:00 5 TABS	3:52:00 TO 4:07:00 15 TABS		2:19:00 TO 2:34:00 15 TABS		35 TABS
SLEEP						13:59:00 TO 15:03:00 27 TABS		27 TABS
RETRO SEQUENCE -90 MIN TO -75 MIN BASED ON MA-6 & MA-7			3:09:08 TO 3:24:08 15 TABS	3:09:08 TO 3:24:08 15 TABS	3:09:08 TO 3:24:08 15 TABS	3:09:08 TO 3:24:08 15 TABS		60 TABS
RETRO SEQUENCE -90 MIN TO -75 MIN BASED ON MA-8					7:22:00 TO 7:37:00 15 TABS	7:22:00 TO 7:37:00 15 TABS	25:00:00 TO 25:15:00 15 TABS	45 TABS
RETRO SEQUENCE -90 MIN TO -75 MIN BASED ON MA-9						32:29:30 TO 32:44:30 15 TABS		15 TABS
REENTRY SEQUENCE -15 MIN TO 0.05 G BASED ON MA-6 & MA-7			4:29:03 TO 4:44:03 15 TABS	4:29:03 TO 4:44:03 15 TABS	4:29:03 TO 4:44:03 15 TABS	4:29:03 TO 4:44:03 15 TABS		60 TABS
REENTRY SEQUENCE -15 MIN TO 0.05 G BASED ON MA-8					8:46:40 TO 9:01:40 15 TABS	8:46:40 TO 9:01:40 15 TABS		30 TABS
REENTRY SEQUENCE -15 MIN TO 0.05 G BASED ON MA-9						33:53:36 TO 34:08:36 15 TABS		15 TABS
0.05 G TO LANDING	00:07:50 TO 00:15:37 47 TABS	00:07:50 TO 00:15:37 47 TABS	4:44:03 TO 4:55:23 68 TABS	4:44:03 TO 4:55:57 72 TABS	9:01:40 TO 9:13:11 70 TABS	34:08:36 TO 34:19:49 68 TABS		372 TABS
POST - LANDING	LANDING +5 MIN (1 MIN SAMPLE, 5 TABS)	LANDING +5 MIN (1 MIN SAMPLE, 5 TABS)	LANDING +5 MIN (1 MIN SAMPLE, 5 TABS)	LANDING +5 MIN (1 MIN SAMPLE, 5 TABS)	LANDING +5 MIN (1 MIN SAMPLE, 5 TABS)	LANDING +5 MIN (1 MIN SAMPLE, 5 TABS)		30 TABS
							TOTAL	1133 TABS

FIGURE 33.—Summary of available data tabs for specific mission phases in the Mercury series.

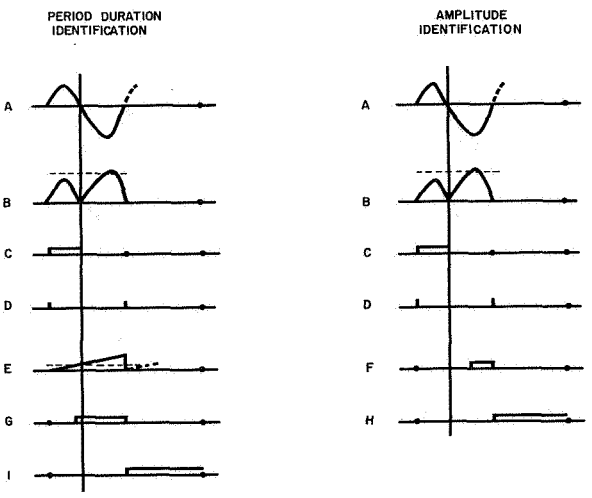


FIGURE 34.—Signal reduction waveforms resulting from the "Yes/No" analysis technique.

the period of the primary signal exceeds the specified threshold. This is registered by the dc voltage in *G*. The voltage in *G* begins at the instant at which the solid line in *E* exceeds the dotted line. This voltage is transferred to *I*, where it remains until information is obtained regarding the next period of the primary signal.

The primary signal is routed through a similar sequence of operations for the amplitude criterion, as illustrated in the right-hand column of figure 34. If the voltage in *B* exceeds the set threshold, the overflow is indicated by the dc trace in *F*. The voltage in *F* is transferred to *H*, where it remains during the processing operation of the next period of the primary signal. The information from *I* and *H* is fed into a multichannel perforator which codes the information on punched tape. The tape, then, represents a continuous record of "yes/no" decisions for the parameters and criteria selected in one or several biomedical signals. It can be used to detect changes of physiological state which appear as changes in the pattern of threshold crossings.

SIGNAL AVERAGING

Signal averaging is a mathematically simple technique that has proved of great benefit to biomedical data analysis. NASA-sponsored studies have employed several variations of this approach. Basically, averaging involves computation of the continuous arithmetic mean over a number of ensembles of a noise-degraded signal. The ensembles represent waveform samples, and the result of the summation is a characteristic or average waveform.

All biomedical measurement signals are contaminated somewhat by distortions caused by artifacts and noise. In extreme cases, a periodic signal may be virtually buried in random noise. Averaging techniques will cancel a good portion of the random noise, while accentuating the harmonic portions of the signal, so that the signal-to-noise ratio is markedly increased. Theoretically, the ratio is improved by the square root of the number of samples included in the sum. (Averaging 16 samples improves the signal-to-noise ratio by a factor of four.) Actually, this improvement may not be fully realized, since the noise may not be entirely random, among other factors. To enhance the signal while canceling noise, some unique shape in the waveform is used as a reference for the summation. In the case of the ECG complex, the *R* wave is generally used as an anchor point. Other points must be found for other periodic biomedical signals. In the case of evoked responses, the repetitive stimulus is often used as a trigger for summing the subsequent responses.

The operational speed of computers has permitted signal averaging to be done on-line. For example, on-line averaging was successfully employed in recording cardiac vibration during exercise in a study reported by C. M. Agress et al. (ref. 4). Previously, high-level noise (associated with subject motion) restricted the recording of chest-wall vibration to static conditions. In the study undertaken by Agress, motion artifacts were essentially removed, so that transitions from rest to exercise, and from exercise to recovery, could be easily identified. Before the averaging technique was applied, records were rendered useless by motion artifact.

HEART RATE BY AUTOCORRELATION PROCESSING

The autocorrelation function can be considered a measure of periodicity. For some time, it has been used to observe hidden periodicities in EEG signals. Recent development work originated and coordinated by NASA's Flight Research Center (FRC) at Edwards Air Force Base, Calif., has demonstrated that this technique is equally valuable in extracting heart rate information from the severely degraded ECG signals common in field records (ref. 5).

Mathematically, the autocorrelation function of a stationary signal $f(t)$ is defined by either of two expressions:

$$\Theta(\tau) = \lim_{T-\infty} 1/2T \int_{-T}^{T} f(t+\tau)\, f(t)\, dt;$$

or

$$\Theta(\tau) = \lim_{T-\infty} 1/2T \int_{-T}^{T} f(t-\tau)\, f(t)\, dt$$

where:

τ = specific time interval, and
$\Theta(\tau)$ = the autocorrelation of $f(t)$ at τ

The definition implies that autocorrelation is a process of shifting the signal with respect to itself, multiplying, and averaging. The autocorrelation function at τ is calculated by shifting $f(t)$ ahead by τ seconds and averaging the product of the original and shifted functions. The same result is obtained if the function is shifted backwards by τ seconds. Consequently, the average product is independent of the direction of the shift. The autocorrelation at $\tau=0$ (no shift) is equal to the average power of the time function, i.e., the average value of the function multiplied by itself. It represents the maximum value of the autocorrelation function, since any shift necessarily reduces the value of the products $f(t) \cdot f(t+\tau)$. In practical applications the period over which the autocorrelation function is calculated is obviously finite, rather than infinite as stated in its definition. (This limitation decreases the reliability of the derived values.)

If a signal contains periodic components, the autocorrelation function contains components of the same periods. This can be seen, since a periodic wave shifted by one period is indistinguishable from the unshifted wave. On the other hand, the autocorrelation component caused by random noise decays exponentially as the time shift increases. If there is a dc component in the signal, there will be a dc component in the autocorrelation which will be independent of the time shift. Consequently,

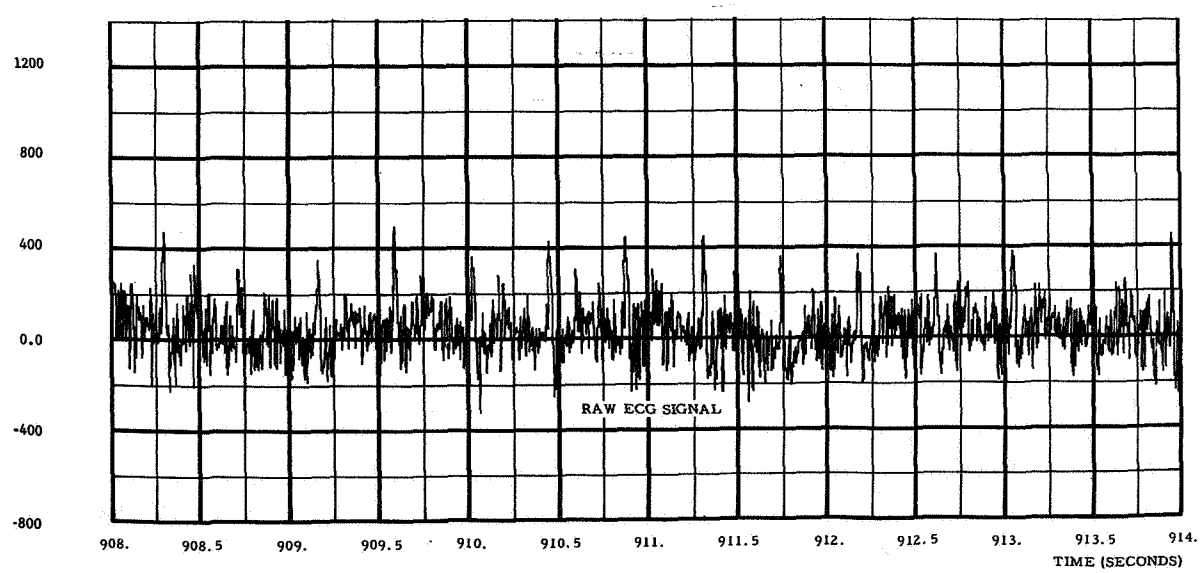


FIGURE 35.—Noisy ECG recording from an X–15 test flight.

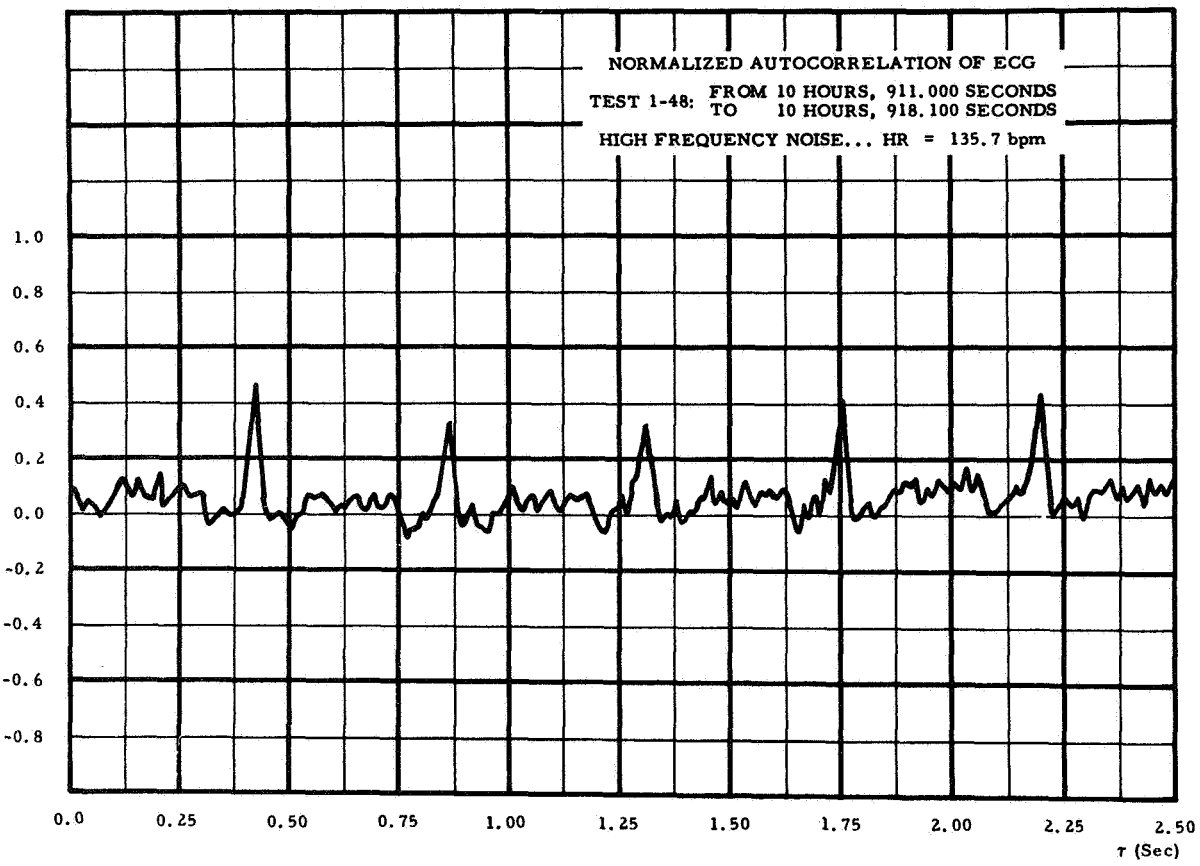


FIGURE 36.—Normalized autocorrelation of noisy ECG recording.

the autocorrelation function is a powerful tool with which to determine the fundamental nature of a recorded biomedical signal, particularly when the signal contains periodic elements masked by random noise.

Degraded ECG signals are of this type, since the ECG complex has a nearly periodic feature. Figure 35 shows a 6-second segment of ECG recording from an X–15 rocket aircraft flight test at NASA/FRC. The signal-to-noise ratio is less than 1.0, the characteristic ECG complex is effectively masked, and it would be virtually impossible to extract heart rate data by standard automatic means. Figure 36 is the autocorrelation function for this record segment. The innate periodicity is easily seen, and it is simple to derive average heart rate for this record interval from the clearly defined spikes. (Heart rate is the reciprocal of the approximately 0.44-second interval between spikes.) Although the autocorrelation function exhibits some similarity to the R wave of the ECG itself, it is not the same. All portions of the ECG signal (P, Q, R, S, and T waves) contribute to the amplitude and shape of the spike in the autocorrelation function. To obtain meaningful results, the autocorrelation parameters must be chosen with regard to the signal under analysis. Detailed studies were undertaken under the direction of NASA/FRC to determine the best parameters (sampling rate, integration time, etc.) for various biomedical signals with a variety of prefiltering arrangements. Partial results are available in reference 5; subsequent NASA reports will contain additional details of the ECG processing procedure.

DIGITAL FILTERING

When signal and noise lie in different frequency bands, a filter can be constructed that eliminates more of the noise than the signal, enchancing the signal-to-noise ratio. Properly programmed, a computer can be made to act as a digital equivalent of a standard analog filter circuit. The digital filter is superior to the analog because it offers complete control of phase shift, provides sharp cutoff, and has bandpass characteristics which can be precisely specified.

Digital filtering can be visualized as an operation that applies preset weighting factors to the frequency components of the incoming signal. The usual design technique is to vary the filter parameters until a best fit, in the least squares sense, is obtained between the actual and the theoretical filter response to an impulse input. Digital filtering has been applied to a variety of biomedical data.

Figures 37 and 38 are samples of ECG records obtained during the X–15 test flight as processed by two digital filtering techniques, in a study sponsored by the NASA Flight Research Center (ref. 5). The lower plot in figure 37 shows the raw ECG signal. The upper plot shows the same signal after it was filtered by a lowpass filter with an 18-Hz cutoff frequency. As can be seen, the noise has been greatly reduced by the filtering operation. Figure 38 shows the ECG signal with a bandpass filter employed. The bandpass was 0.5 to 20 Hz. This filter however, removed the dc component as well as a good part of the respiration effect. The latter is particularly

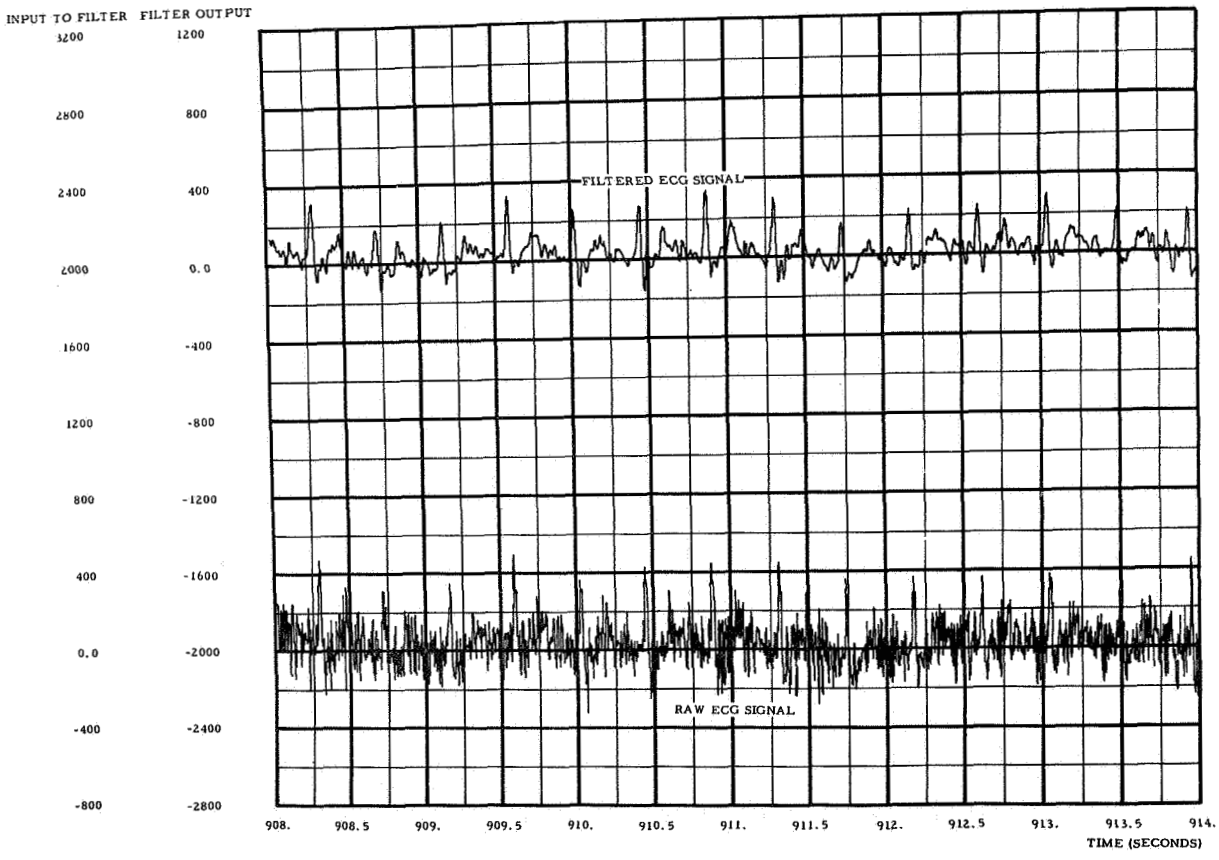


FIGURE 37.—Effect of low-pass (18-Hz) digital filtering on a noisy ECG signal.

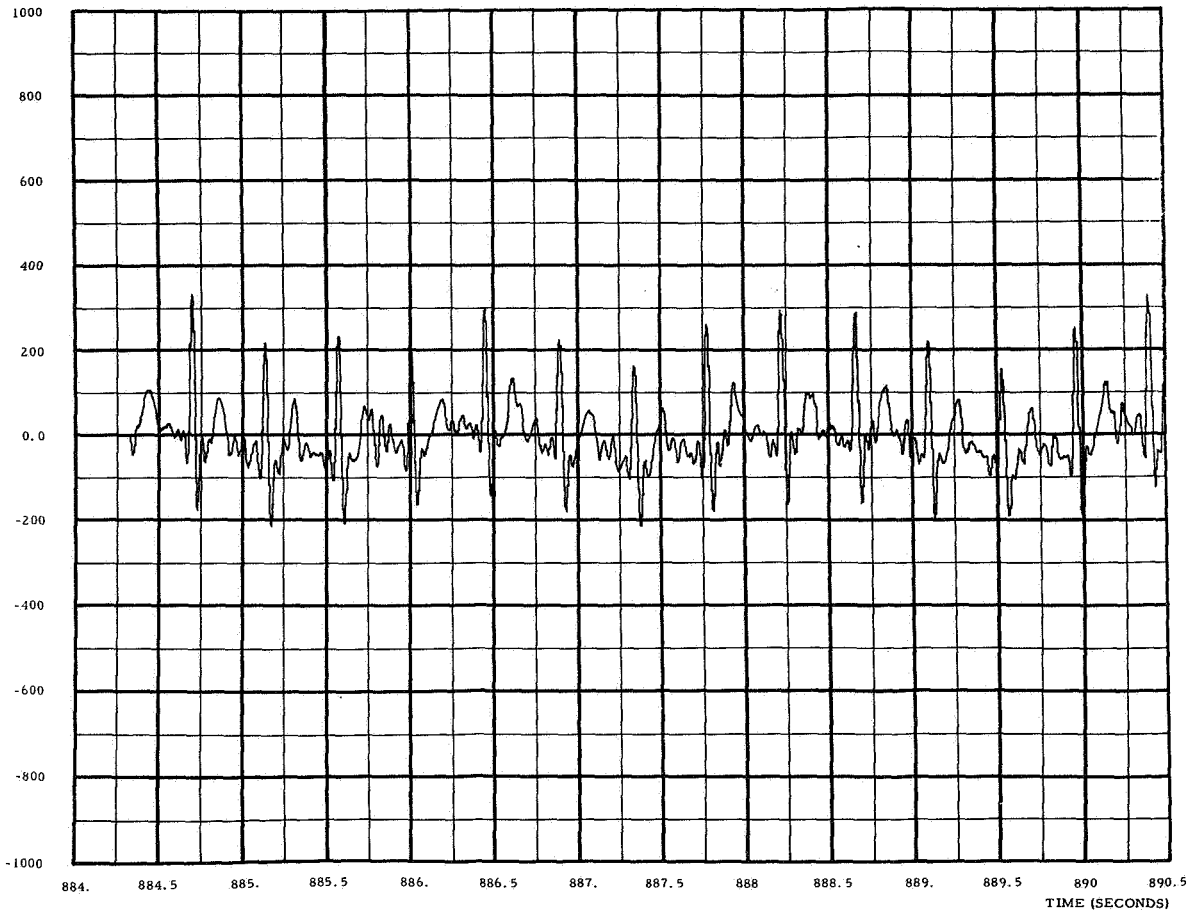


FIGURE 38.—Noisy ECG signal after digital bandpass (0.5- to 20-Hz) filtering.

important when the R wave is used as a trigger in a cardiotachometer or as an identification mark in computer ECG analysis.

POWER SPECTRAL DENSITY ANALYSIS

The power spectral density of a signal gives the power density (watts/Hz) as a function of frequency (Hz). The spectral density is the Fourier transform of the autocorrelation function. Where the autocorrelation function yields information in the time domain, the spectral density function contains the same information in the frequency domain. The power spectrum of a purely sinusoidal signal is a sharp spike located in a differential interval around the signal frequency, i.e. Δf. This peak occurs because all signal power is in the differential Δf and is zero at all others. The other extreme is a white noise signal, which can be thought of as containing an infinite number of equally contributing sinusoidal signals. White noise has a flat power density, since its power is uniformly distributed across the frequency spectrum. Many biomedical signals occupy an intermediate position between these two extremes.

Figure 39 shows the autocorrelation and relative power functions of an ECG obtained during an X–15 flight at NASA's FRC (ref. 5). The spectral peak is at the second harmonic of the fundamental R–R frequency. The main intelligence bandwidth of the flight ECG signal seems to be from about 3 to 30 Hz,

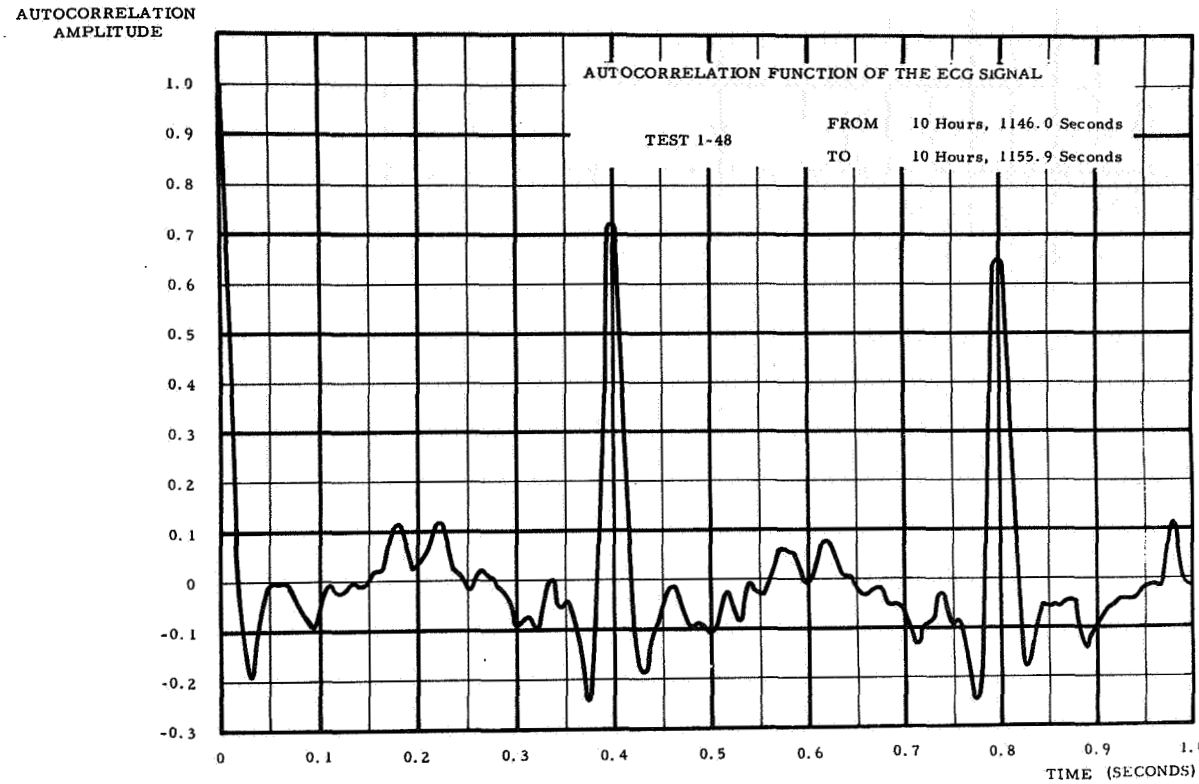


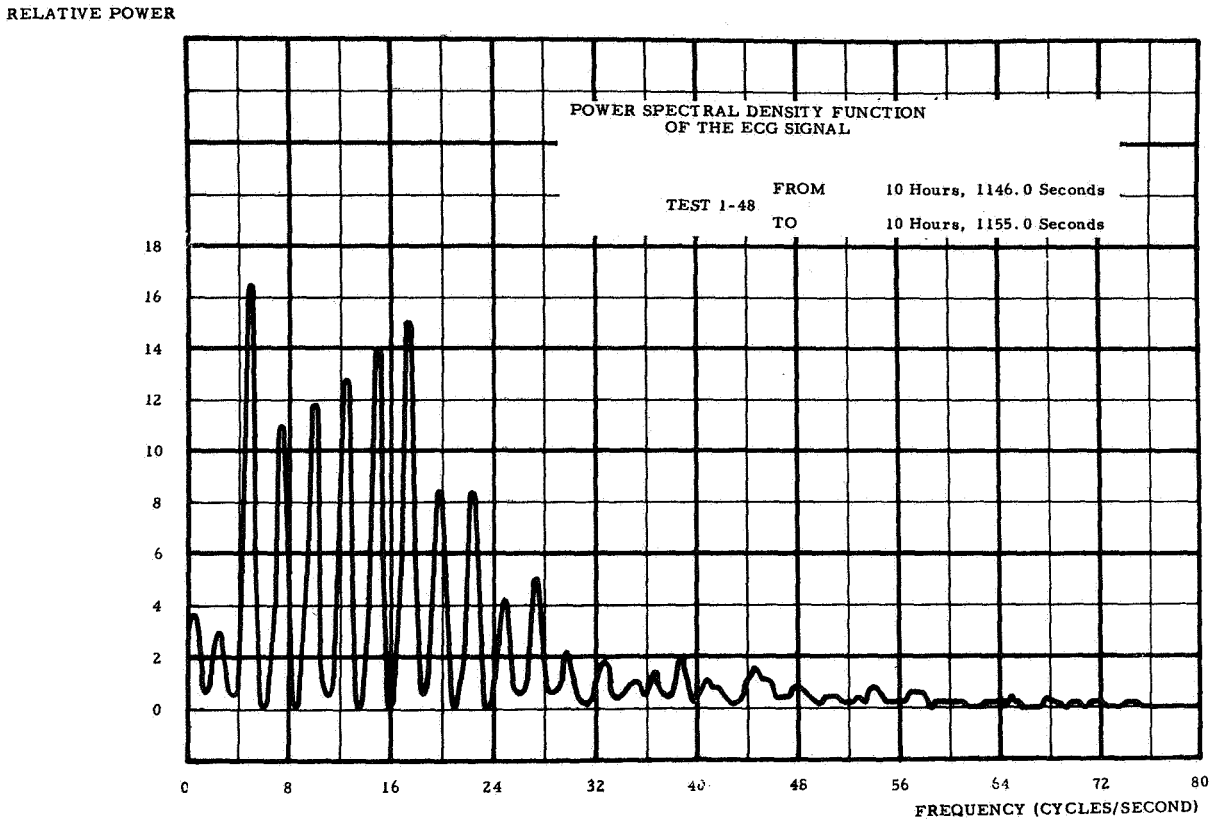
FIGURE 39.—Autocorrelation function and corresponding

although significant noise power appears at frequencies as high as twice the bandwidth of the main intelligence. Important information regarding the harmonic and statistical structure of the ECG signal is obtained through the power spectral density analysis. In addition, the technique indicates the demarkation of signal and noise frequencies, data necessary for effective design of signal conditioners (see chapter 4).

AUTOSPECTROGRAM CONTOUR MAPS

In many situations, the autospectrogram (power spectral density) of a physiological signal changes with time. Describing these changes concisely and clearly presents a major problem. A contour mapping technique has been developed by Walter and Brown of the Brain Research Institute (BRI), UCLA (refs. 6 through 10), which largely overcomes the difficulties associated with the presentation of such biomedical data.

Figure 40 shows the construction of a contour map using EEG data taken from a normal scalp over a period of 480 seconds (ref. 9). The contour map is made up of a sequence of successive autospectrograms. The left side of figure 40 shows the first autospectrogram of the sequence, representing the first 12 seconds of the total period. The contour map itself is shown on the right side of the figure. The horizontal and vertical axes of the map represent time and frequency, respectively. The shaded and cross shaded areas indicate intensity of the spectral density function $[\mu V]^2/Hz$). Two selected intensity levels are marked by dotted lines on the autospectrogram. Intersections between the dotted lines and the autospectrogram were mapped into the time-frequency



power spectral density function of the ECG signal.

plane of the contour map. Repeating the same procedure for each successive autospectrogram formed the contours shown on the map; each contour is loci of points of the same power intensity. Here only two intensity levels were chosen, although the number of levels is arbitrary. Usually the contour intensity levels are selected at logarithmic intervals; in this way, the contours of the map represent the logarithms of power intensity. The *H* and *L* letters represent the highest and lowest points in their immediate neighborhoods. This gives the interpreter a better feeling for the mountainous nature of the surface.

Figure 41 shows an EEG autospectrogram contour map obtained from a chimpanzee during 20 minutes of a Biosatellite performance simulation (refs. 1 and 6). The extent to which the EEG has been compressed in this contour map is illustrated by the fact that it contains 100 autospectrograms, each requiring many thousand multiplications.

Changes in the spectral intensity as a function of frequency and time on the map can readily be related to the various states of the subject, as well as to his transition from one state to another. In this case, it is easy to observe that most of the power is concentrated below 5 Hz. The record begins with a high power concentration at about 2 Hz, which is interpreted as a drowsy state. Next the chimpanzee changes from drowsiness to sleep, which is indicated by an increase of 1- to 2-Hz power intensity between the ninth and fifteenth minute. Finally, the chimpanzee awakes, as indicated by the disappearance of the concentrated power at the low frequencies. The example shows the effectiveness of the intensity contour mapping technique as an aid to interpreting data by visual inspection.

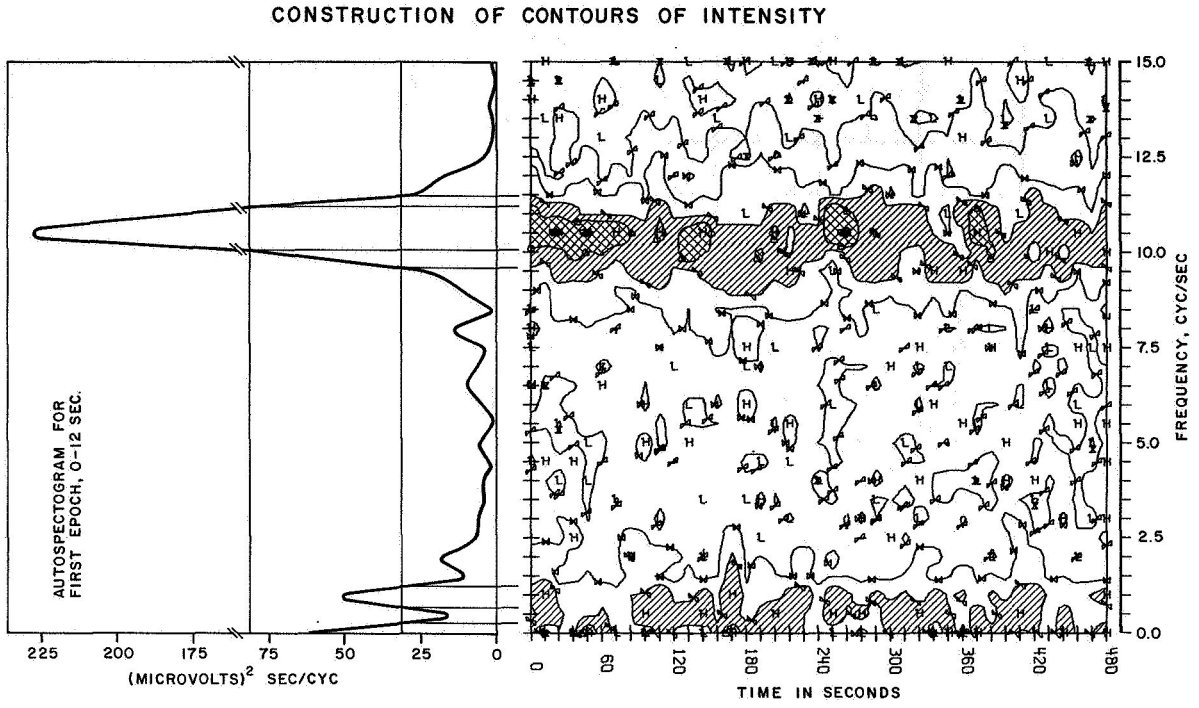


FIGURE 40.—Construction on an EEG autospectrogram intensity contour map.

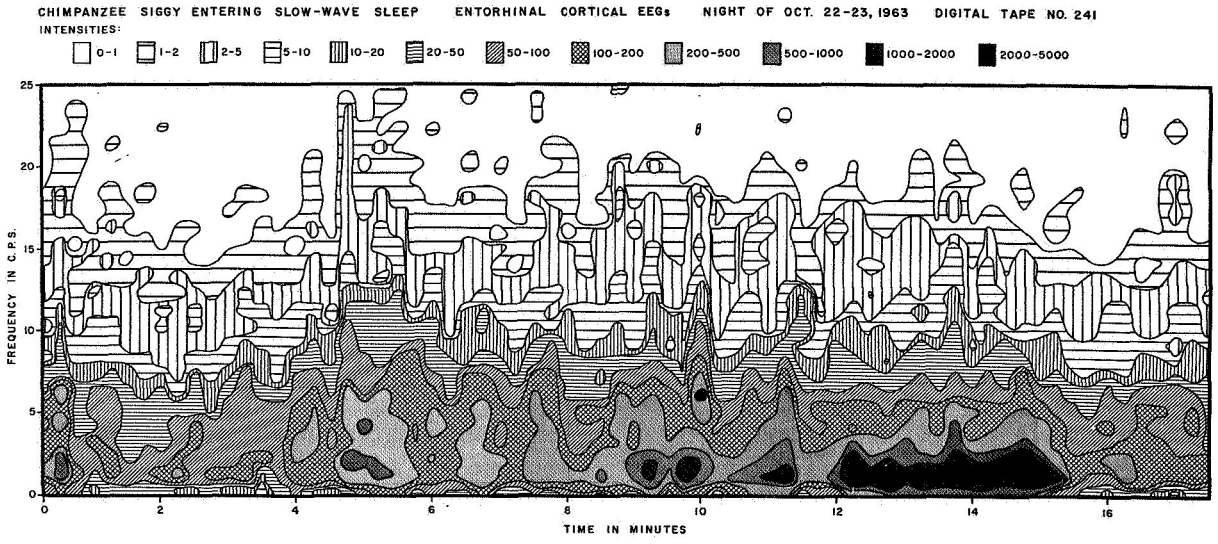


FIGURE 41.—EEG autospectrogram contour map obtained from a chimpanzee during 20 minutes of biosatellite performance simulation.

COHERENCE CONTOUR MAPS

The coherence contour map is identical to the autospectrogram contour map, except that the vertical axis represents coherence instead of spectral intensity. The coherence contour map has been used by Walter and his col-

leagues to extract information regarding brain wave activity originating in different regions of the brain. This is possible because of the unusual properties of the coherence function.

Basically the coherence function is a normalized cross spectral function, the magnitude of which varies between 0 and 1. It serves as a measure of interdependence of the time function $X(t)$ and $Y(t)$. That is, if both time functions are random waves, having no dc components, and are derived from independent sources, the magnitude of the cross spectral function, as well as the magnitude of the coherence function, is identically zero. The magnitude of the coherence function is defined by the expression:

$$\mathrm{COH}(f) = \frac{\mathrm{MAGS}^2(f)}{\mathrm{ASX}(f)\ \mathrm{ASY}(f)}$$

where:

$\mathrm{COH}(f)$ = the magnitude of the coherence function at frequency f,

$\mathrm{MAGS}(f)$ = the mean cross spectral magnitude of the functions $X(t)$ and $Y(t)$ at frequency f,

$\mathrm{ASX}(f)$ = the autospectrum of time functional $X(t)$ at frequency f, and

$\mathrm{ASY}(f)$ = the autospectrum of time function $Y(t)$ at frequency f.

It has been found empirically that a coherence greater than 0.5 indicates a significant interrelationship between two time functions or two signal sources.

Coherence function analysis has been applied to a wide variety of EEG data at BRI (refs. 7, 8, and 11). Coherence plots were obtained by computing the coherence function for two or more wave trains over a restricted frequency band. These plots gave information regarding the phase relationship and shared frequencies between EEG signals originating simultaneously in different regions of the brain. Relationships were obtained for a variety of activities, leading to quantitative study of transitions occurring in the brain during tasks such as auditory vigilance and visual discrimination. Sequences of coherence plots were mapped into coherence contour maps, in the same fashion that autospectrograms were mapped into intensity contour maps. If intensity contour maps are available for a pair of simultaneously recorded wave trains, they can be directly transformed into a coherence contour map.

Figure 42 shows coherence contours generated from pairs of EEG wave trains (ref. 9). The two arrows entering each map identify the contributing brain regions. The circles in the contours mark the time-frequency loci of significant coherence between the corresponding brain regions.

Figure 43 is a sample from an analysis performed at BRI on 55 hours of EEG data recorded from astronaut Borman during Gemini VII (refs. 11 and 12). Analysis included calculation of autospectral and cross spectral distributions, as well as coherence functions. The map at the left shows autospectrogram contours for one EEG lead; the center map contains the same information for a second lead; the map at the right is a coherence plot, which provides information regarding the interaction between the two brain regions at different frequency bands during this flight period. Results obtained from the flight data were compared, utilizing power spectra techniques, with baseline data that were collected for the same subject in a Gemini flight simulator. The study revealed anticipatory and arousal states before launch, orientation reactions during initial exposure to weightlessness, sleep periods, and various other states of alertness. Note the "elastic" time base used in the contour plots. This technique allows expansion of the base to present selected periods of activity in greater detail than those of lesser interest. Greater compression of computed results is obtained without loss of significant detail.

CONTOUROGRAPH TECHNIQUES

The contourograph is a three-dimensional display that provides a perspective view of successive waveforms or functions in place of the plane view presented by contour maps. The technique was described by G. N. Webb at Johns Hopkins University (ref. 13). In his work, successive ECG complexes were recorded

FIGURE 42.—Contours of coherence for pairs of EEG signals.

slightly above one another, as shown in figure 44. The complexes were displayed on a cathode-ray storage tube and the tube beam intensity modulated so that it became brighter as signal intensity within the ECG complex increased. This technique created a display with a three-dimensional appearance of hills and valleys, on which it was easy to see changes in waveform shape, and R to R distance.

Improvements on this technique were developed by S. K. Burns et al. at the Research Laboratory of Electronics, M.I.T., under partial NASA sponsorship[1] (ref. 14). These workers modified the contourogram display

[1] The research was supported by NASA (Grant NSG–496), National Institutes of Health (Grant 1 PO1 GM–14940–01), and the Joint Services Electronics Program (Contract DA28–043–AMC–02536 (E)).

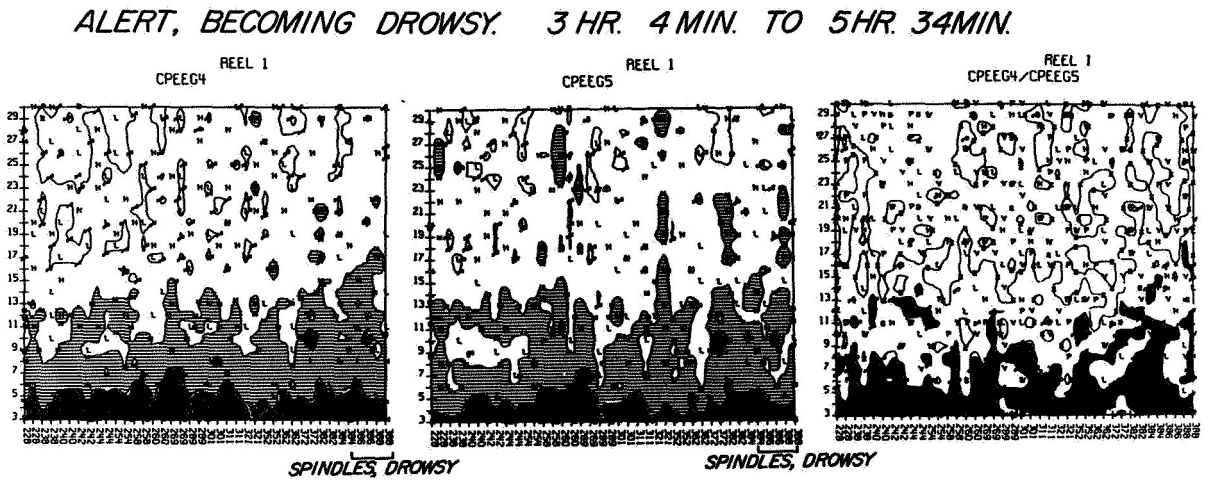


FIGURE 43.—Autospectrum and coherence contours during 2½ hours of Gemini GT–7 mission.

and applied the technique to waveform averages instead of individual waveforms. The display modification is illustrated in figure 44b. It involves slanting the axis representing the time associated with successive complexes, which heightens the three-dimensional quality of the display.

Figure 45 is a photographic superimposition of 512 average click-evoked responses, representing the cortical potentials of a rat. Each of the average responses was computed from 120 evoked potentials. To provide a "smooth" transition from one average to another, a "moving average" technique was employed. That is, each average of 120 responses was displaced by an interval corresponding to only 15 responses from the preceding average. In this fashion, 105 of the evoked potentials included in each average also enter into the adjacent one. The "smoothness" of the surface can be controlled by varying the amount by which adjacent averages of the signal complexes overlap. Chlorpromazine was administered at the point marked by an arrow; the subsequent change in cortical potential is distinctly seen. The contourogram technique is widely applicable and could, in fact, be used with the power spectral density or coherence plots discussed earlier.

ADDITIONAL CONTRIBUTIONS

NASA's concern with increasing the amount of physiological information extracted from noise-degraded signals has brought about several improvements in signal processing techniques. The ECG preprocessing unit and the cardiac and respiration monitors briefly outlined below are a result of NASA's efforts in this area. Improvements in signal processing have been supplemented by improved analysis techniques, many of which were presented in previous sections of this survey. The additional contribution presented here deals with the first and second derivative of rate data, such as heart rate and respiration rate.

(1) An electrocardiogram preprocessing unit was developed for NASA at the Texas Institute for Rehabilitation and Research (ref. 15). This unit provides a fixed pulse output for each heart beat and is unresponsive to a wide variety of false trigger signals. Consequently, the unit is useful where electrocardiograms are associated with noise caused by subject exercise, flight conditions, or other disturbances.

The pulse output of the unit can be used as a trigger for a cardiotachometer circuit, or can be digitized and fed into a computer for further analysis. Figure 46 shows the block diagram of the electrocardiogram processing unit. The input signal is fed to a bandpass filter which is tuned to the frequency of the *QRS* complex and rejects frequency components responsible for noise and artifacts. The signal is then processed through a hybrid full-wave

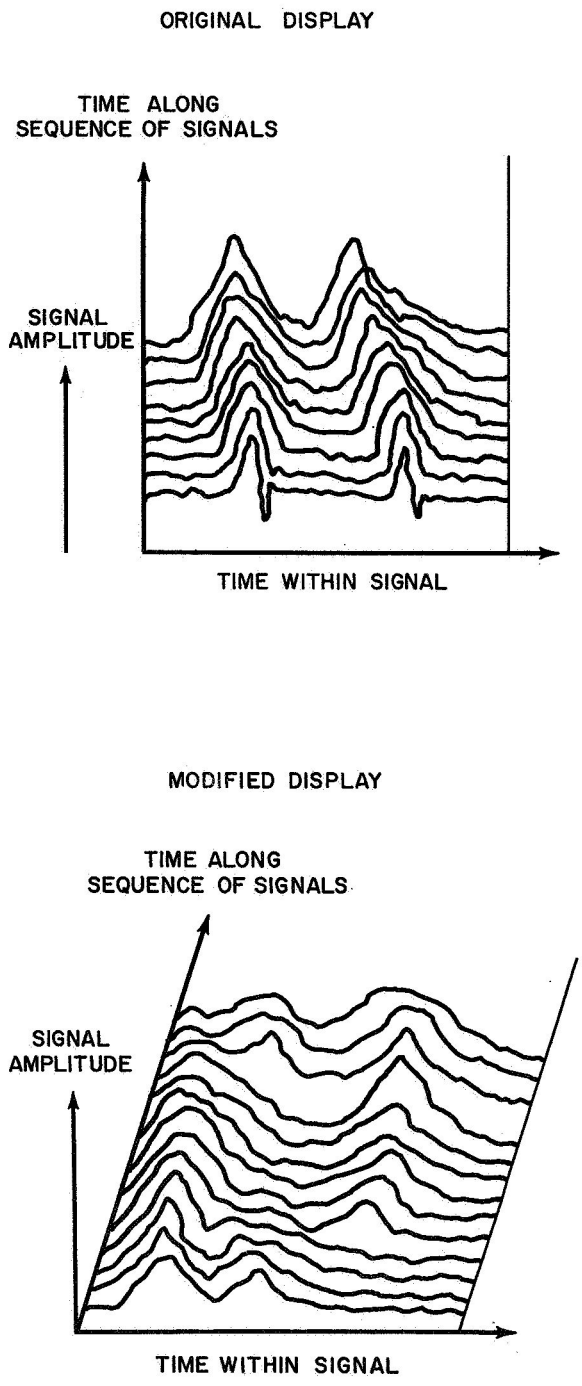


FIGURE 44.—Contourogram display techniques.

rectifier, which triggers a one-shot multivibrator circuit to give a pulsed output.

Figure 47 shows an ECG wave before filtering and after filtering, and the resulting pulse output. In this case, the pulse output is not affected by the slow wave artifact present in the ECG; this is caused by the filter which reduces the artifact to an amplitude insufficient to trigger the multivibrator.

(2) Advanced cardiac and respiration rate monitors for use on Gemini spaceflights were developed and fabricated for NASA by Bendix-Pacific Division (ref. 16). The monitors provide instantaneous heart rate, instantaneous respiration rate, and average respiration rate. Values are displayed on analog meters and recorded on strip charts. Signal preprocessing is carried out in a manner like that described for the preprocessing unit above. These monitors have a novel circuit feature: an active, nonlinear filter and integrator. The combined effect of these circuits is to reduce effects caused by discontinuity of signal resulting from loss of telemetry and other artifact noise.

(3) The time rate of change of such derived variables as heart rate and respiration rate is of interest in medical monitoring. In computing this quantity, however, conventional differ-

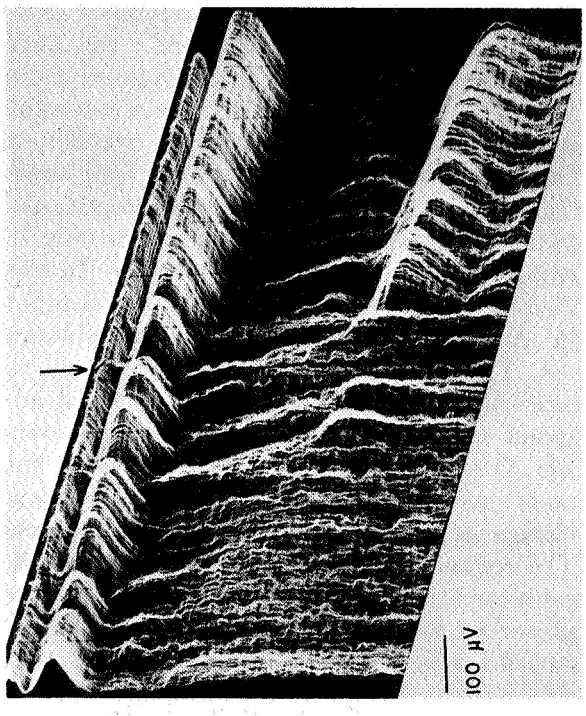


FIGURE 45.—Contourogram display of average evoked cortical potentials of partially restrained rat.

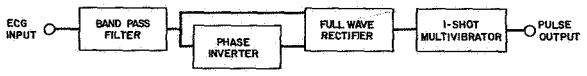


FIGURE 46.—Block diagram of ECG preprocessor developed at the Texas Institute for Rehabilitation and Research.

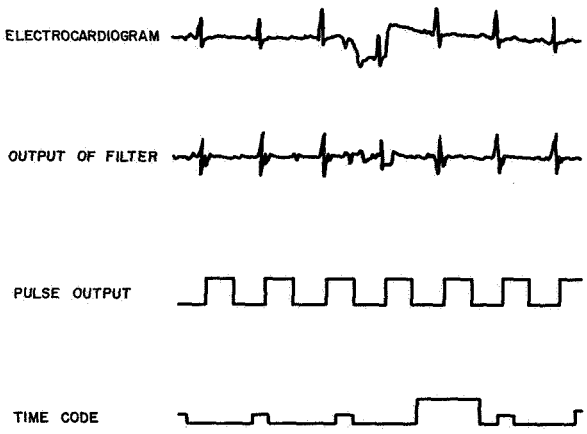


FIGURE 47.—Response of the Texas Institute ECG preprocessor to a slow wave artifact.

entiation (from the calculus) has to be modified. This is because differential calculus assumes continuous measurements, which is not the case in heart rate and respiratory rate determinations and also because it is difficult to fit smooth curves to the irregular instantaneous rate data. According to J. F. Lindsey (ref. 1), studies carried out at NASA by J. C. Townsend (refs. 17 and 18) show how to apply differentiation procedures to variables such as heart rate or respiration rate. The procedures yield rate of change and rate of rate of change, which can be used as new physiological parameters. These parameters are reported to be sensitive indices of astronaut adaptability to spaceflight conditions.

APPLICATION EVALUATION

Current technology has made it relatively simple for the biomedical investigator to collect floods of data. Accordingly, automated techniques for condensing, summarizing, and extracting hidden information from these data have become essential. NASA contributions to data analysis in bioinstrumentation systems apply directly to two major areas of clinical medicine: mass data processing and automated signal analysis. These areas share the objective of revealing aspects of the data not immediately obvious to the physician. Both are steps toward automated diagnosis and thus are closely connected to such new medical techniques as intensive care monitoring, continuous monitoring of ambulatory heart patients, multiphasic testing, etc.

To a large extent, however, many of the techniques discussed in this chapter and in the preceding chapter depend on the digital computer. While the value of computers in all phases of medicine is unchallenged today, a majority of the medical community remains outside the computer fold. This is mainly because previous development has centered on large, high-powered, and expensive computer installations, like those at Manned Spacecraft Center and many universities. The recent appearance of small, fast, and relatively inexpensive computers promises to extend the benefits of automatic data processing. In particular, the small computer appears well suited to the various hospital subdivisions which have found computer use uneconomical up to now. Its introduction may greatly extend the direct application of many of NASA's contributions.

A small computer is defined as such on the basis of its data processing capacity, data storage capacity, and price. With modern circuit construction techniques, it may generally be small in size. Compared to the more powerful computers, the small machine (1) utilizes a shorter word length (i.e., numbers are carried to less significant figures); (2) is limited in the number of operations it can do simultaneously; and (3) provides a smaller fast memory. The operation of small and large computers is similar; the small computer may perform its constituent arithmetic operations nearly as fast as the big machines and match them in programming sophistication.

The combination of adequate storage capability and high computing speed makes the small computer attractive in many biomedical data processing situations. For example, an-

alysis has shown that the small computer can effectively handle advanced monitoring operations in the surgical recovery unit and such special situations as shock management (see ref. 11, chapter 5). Small special-purpose computers have been constructed to provide continuous auto and cross correlation, as well as spectral analysis, indicating that this type of operation is also possible on the small, general purpose, programmable machines.

Advanced NASA data handling and processing techniques described in the last two chapters may soon be applied to nonaerospace situations at reasonable cost. The transition from large-computer to small-computer implementation of these techniques will be limited only by the imagination of bioinstrumentation system designers.

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CHAPTER 7

Advances in Measurement Technique for Use in the Field

NASA has sought laboratory-quality measurements under field conditions. Thus, in a sense, most of the NASA-sponsored bioinstrumentation represents advances in field measurement technique. Several developments, however, are outstanding; some because they bring to field observation methods formerly available only in the laboratory, and some because they demonstrate the solution of particularly difficult measurement problems.

Three examples are presented in this chapter. The flight adaptation of impedance pneumography for respiratory recording illustrates a two-phase attack, through scientific research and equipment design, on a basic biomedical measurement problem. The NASA spray-on electrodes illustrate a novel approach to sensor attachment obstacles encountered in an ambitious and successful program of pilot monitoring. Finally, development of the in-flight mass spectrometer represents an engineering tour-de-force, which potentially brings a valuable laboratory analytical technique to the field environment.

IMPEDANCE PNEUMOGRAPHY

When planning spaceflight monitoring, NASA recognized the need for continuous respiratory data as an indication of physiological condition. Available techniques such as pneumographs, pneumotachographs, spirometers, strain gage devices, or thermistor sensors were either unreliable or encumbering. Accordingly, NASA turned to the then little-known technique of impedance pneumography. Through continual study, evaluation, and engineering development, this method was improved to the point of successful application under the most arduous flight conditions.

Impedance pneumography constitutes an indirect means of measuring respiratory volume. The method is based on the observed relationship between transthoracic impedance and the volume of inspired air. During respiration the many tissues of the thorax, which include fat, muscle, fluids and lung tissues, are stretched, and the electrical impedance of the thorax changes. If a constant current is introduced into the tissues, the voltage drop across the thorax will fluctuate together with the respiratory movements. This phenomenon was observed as early as 1935 and has since been studied by a number of investigators (ref. 1). Although the exact cause of the impedance change is still unknown, a good deal of empirical data has been acquired that permits fairly confident instrumentation design.

This measurement method does not require that the patient wear a facemask. Nor is a separate air system needed. The technique is insensitive to changes in barometric pressure, temperature, or gravitational forces. Transducers consist simply of a pair of electrodes located on both sides of the thorax, such that an electrocardiogram may also be obtained from the same electrodes (ref. 2).

A representative impedance pneumograph is shown in figure 48. The equipment consists of three circuit modules: an oscillator, an amplifier, and a demodulator. The input terminals *a* and *b* encompass an overall impedance

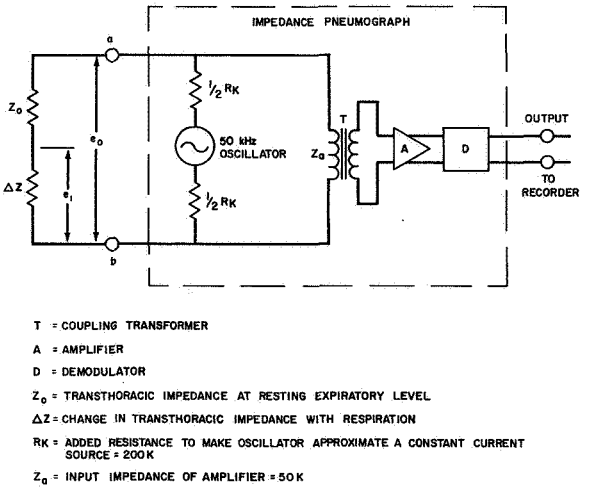

FIGURE 48.—Impedance pneumograph block diagram.

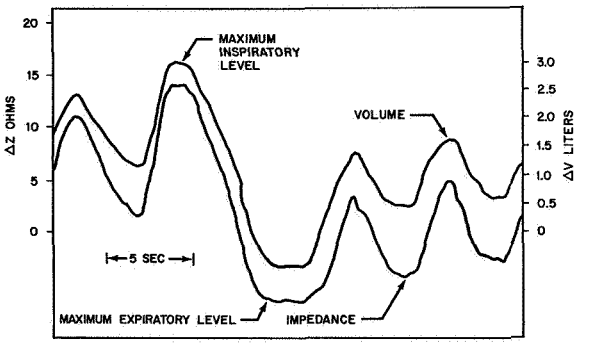

FIGURE 49.—Simultaneous tracings of respiratory volume and transthoracic impedance for a seated male subject.

$Z_0+\Delta Z$. Z_0 represents the transthoracic impedance measured at rest, and ΔZ represents the impedance change during respiration. The output voltage of the oscillator is applied across the subject's thorax and the transformer input. If the output impedance of the oscillator is much greater than $Z+\Delta Z$, then the voltage drop across the transformer is a function of thoracic impedance, $Z+\Delta Z$. Fluctuation in thoracic impedance modulates the oscillator signal. The modulated signal is amplified by the tuned amplifier and demodulated, yielding an analog representation of respiratory movement. The two basic variables in this system are the frequency of operation and the location of the electrodes on the subject.

A study of the parameters involved in pneumographic measurements (ref. 3) indicates that the frequency of the applied current must be high enough to avoid stimulating the subject; that is, it should be well above the highest frequency found in bioelectric signals. Experiments showed that pneumograph measurement can be made over a range from 20 to 100 kHz. It was found that the placement of the electrodes on the chest determines the amount of impedance change sensed during each breath. Moreover, location of the electrodes close to the sixth rib yields the highest impedance change per breath and, therefore, is most suitable for pneumographic recording.

A NASA-sponsored study at Baylor University quantitatively determined the relationship between the variation in transthoracic impedance during respiration and the volume of inspired air (ref. 4). A typical impedance volume record is shown in figure 49. A large number of such records was obtained at fast recording speeds; no lag was observed between the fluctuation of volume $W\Delta V$ and impedance, ΔZ. Using random samples of ΔV and ΔZ, correlation coefficients, regression lines, and standard errors were calculated. The data indicated a close correlation between the physical measurements of the subject, such as size, and weight, and the ratio $\Delta Z/\Delta V$. The study concluded that knowing these measurements one can determine the volume of inspired air within ± 0.166 liter in 95 out of 100 cases.

The relationship between the transthoracic impedance and the impressed current frequency was examined in the same study. Data were obtained from a single subject with electrodes placed on the midaxillary line at the xiphoid level. Resting expiratory level (Z_0) decreased with increasing frequency throughout the range of 50 to 600 kHz. However, through this range the fluctuation of impedance caused by inspiration was constant at 23 ohms. Thus, it appeared that ΔZ was frequency independent and that the fluctuation in the impedance is basically resistive.

The first NASA impedance pneumograph system was developed by McDonnell Aircraft

Corp. on the basis of the work done by Geddes and his colleagues at Baylor University. The components of the McDonnell pneumograph were located beside the pilot and were connected to the electrodes by wire. This system was used throughout the Mercury program, starting with the second flight. Although the system produced excellent impedance recordings, it had some shortcomings in flight because of noise pickup by the electrode leads.

The problem was solved in the NASA-sponsored development of a miniaturized impedance pneumograph signal conditioner (see chapters 4 and 8). The signal conditioner weighed 50 grams and was mounted inside the pilot's suit. The operating frequency of this system was set at 50 kHz. In use, electrocardiogram signals were recorded from the same electrodes. The ECG signals were obtained at a frequency of 320 samples/sec and passed through a lowpass amplifier with an upper frequency limit of 100 Hz. The new instrument was used successfully on the Gemini flights and has been further improved for the forthcoming Apollo program. To date, however, NASA has depended on the impedance pneumograph for qualitative rather than quantitative indications of respiratory volume. This is because the conditions of long-term spaceflight preclude optimal electrode placement and the necessary calibration of the impedance signals.

SPRAY-ON ELECTRODES

The objective of a project at the NASA Flight Research Center at Edwards Air Force Base, is to obtain in-flight physiological information daily on students at the USAF Aerospace Research Pilot School. To do this, the student pilots must be quickly prepared for ECG recording "on the run," as they enter their aircraft. The electrodes used must operate reliably under the flight conditions and must not interfere in any way with the movement or comfort of the pilot subject. The requirements specified were (ref. 5):

(1) Neither the electrodes nor the electrode wire should be felt by the subject.

(2) Electrodes must be resistant to motion artifact.

(3) Skin irritation must not result from frequent application of the electrodes.

(4) Shaving must not be a part of the procedure of applying electrodes.

(5) Application of an electrode should take less than 30 seconds.

At the Flight Research Center, these requirements were met by the development of novel spray-on electrodes, which resist motion artifact and can be applied to the skin in a relatively short time.[1] The electrodes are composed of an air-drying, electrically conductive cement that can be applied to the skin by a spray gun or an aerosol process. The conductive cement is a mixture of a commercially available household cement, silver powder, and acetone (refs. 5, 6, and 7).

Figure 50 illustrates the steps in applying a spray-on dry electrode. The spray gun (A) is a modified atomizer assembly with two valves and a glass container for the liquid cement mixture. An air hose in the spray gun is used to dry the cement. A special barrel (B) with a slit tab on the end holds the fine electrode lead, which is disengaged by a spring-loaded release rod. The barrel confines application of the conductive cement mixture to a circular area the size of a half dollar. A similar barrel has been fabricated to fit aerosol cans filled with the conductive spray mixture (C). For effective application of the electrodes, the selected skin area must be cleaned with an electric toothbrush and electrode jelly (D). The residual jelly is then removed and a fresh thin film of jelly is wiped onto the prepared skin area. Conductive cement is sprayed over the jelly film to capture an end of the lead wire and to form the circular electrode on the skin (E). The electrode is finally air dried and coated with commercially available insulating cement released from an aerosol can (F). The finished electrodes are shown in figure 51; they are less than twenty thousandths of an inch thick, and their con-

[1] In a cooperative effort of NASA personnel and a field team from Spacelabs, Inc.

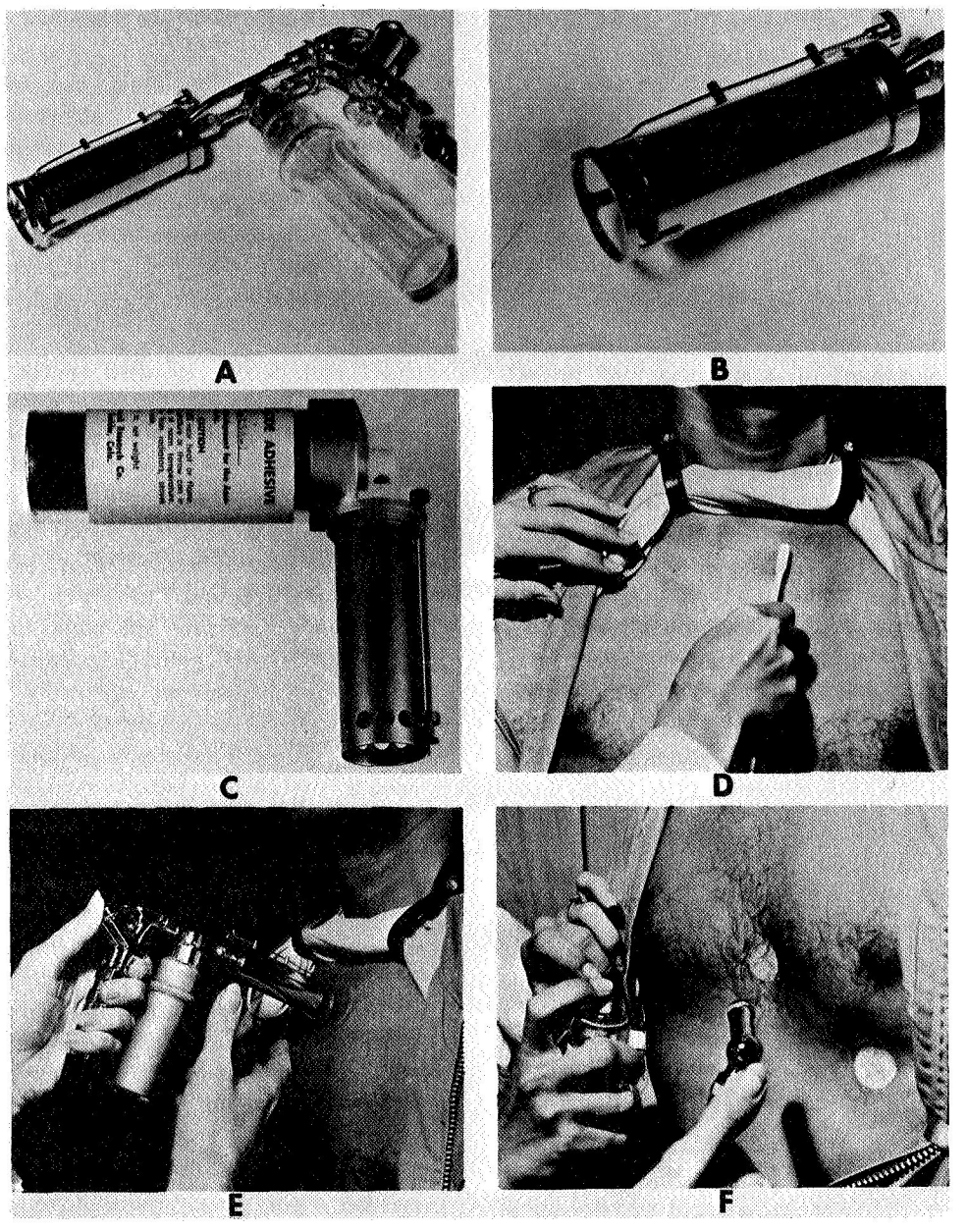

FIGURE 50.—Steps in the application of NASA/FRC spray-on electrodes.

necting wires are approximately the diameter of a human hair.

Experience to date has shown that the time required to connect one spray-on electrode to the subject is 20 seconds; complete attachment of three electrodes routinely takes only about 3 minutes. This is quite short in comparison to the time required to attach conventional electrodes. Skin shaving is not required before the electrodes are applied. Spray-on electrodes have been attached to several hundred subjects, and no cases of skin irritation, folliculities, or contact dermatitis have been noted (ref. 5). In addition to recording well over 1200 hours of data (as of August 1966) at the Flight Research Center, the dry elec-

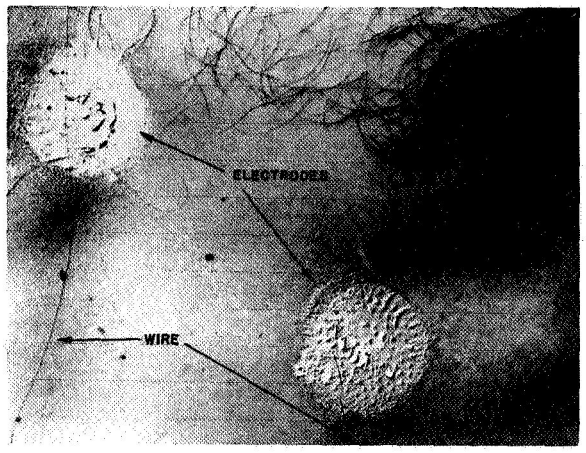

FIGURE 51.—NASA/FRC spray-on electrodes after application.

trodes have been used to obtain heart rate data from Navy carrier pilots in combat over Vietnam (refs. 8 and 9).

The major disadvantage of the dry electrodes is their high impedance, which ranges between 75 and 100 kilohms. High impedance increases the susceptibility of the monitoring system to noise, reduces the gain of the system, and attenuates the low frequency components of the recorded signal. A high input impedance amplifier overcomes most of these difficulties. Experiments have indicated that an amplifier input impedance of at least 2 megohms is necessary to reproduce the ECG waveform without distortion (ref. 5). With such an amplifier, ECG tracings, as illustrated in figure 52, equal those obtained with conventional wet electrodes. Figure 52 also indicates that the dry electrodes are suitable for impedance pneumography.

MINIATURIZED MASS SPECTROMETER

Another developmental program sponsored by the NASA Flight Reseach center is for the construction of a small mass spectrometer, capable of use in a high-performance aircraft or a space capsule (ref. 10). The objective of the program is to permit analysis of expired gases, particularly alveolar samples, under dynamic field conditions. It is part of a general NASA effort directed toward improving existing gas sensors such as the polarographic O_2 sensor and the infrared CO_2 sensor. However, these sensors are restricted to specific gases, and generally are limited in their time of response to changes in gas concentration.

The mass spectrometer, on the other hand, is characterized by an inherently rapid response. This is highly useful for breath-to-breath recording (ref. 9), since the partial pressures of O_2 and CO_2 change rapidly throughout a single breath. Also, in normal individuals the O_2 and the CO_2 partial pressures during the last 1/10th of a second of a

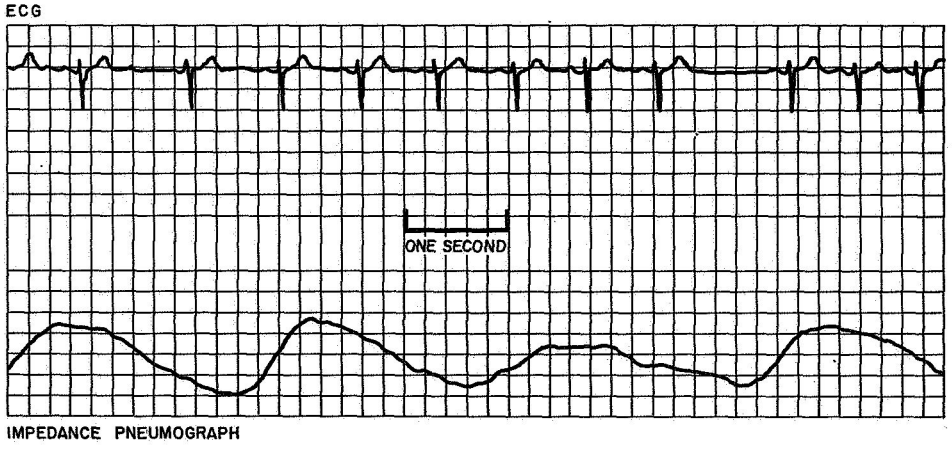

FIGURE 52.—Tracings obtained with NASA/FRC spray-on electrodes.

single expiration will closely approximate those of the alveolar air and, accordingly, those of arterial oxygen and carbon dioxide. To detect the alveolar O_2 and CO_2 pressures continuously and accurately, it is necessary to perform the entire gas analysis within the critical period of 0.1 second—a requirement that can readily be satisfied by the mass spectrometer. The ability of the mass spectrometer to analyze many gases simultaneously gives it the added feature of detecting and measuring gases whose presence might be unanticipated or unknown.

The mass spectrometer analyzes a gas mixture by separating it into its components on the basis of mass; chemical properties are not utilized. A wide variety of mass spectrometers has been developed. They differ in physical structure and in mass detection configurations; the operating principle, however, is the same. In each, gas molecules are converted to positive ions and accelerated by the application of an electric field. Then, one of several methods is applied to a trajectile movement path. The various ions are split into different trajectories according to their mass—the heavier ions having the longer paths. At the end of their trajectories, the ions of each mass group impinge on separate collector buckets, producing an electrical current in proportion to their concentration in the sample.

The basic problems in adapting mass spectrometry to in-flight gas analysis are weight and size. Commercial mass spectrometers normally weigh several hundred pounds and occupy a good part of a laboratory room. These difficulties were overcome in the miniature, double-focusing mass spectrometer developed to the specifications of the NASA Flight Research Center (ref. 11).[2] The NASA/FRC instrument weighs 28 pounds, measures 10×11×11 inches and, for its space applications, requires no vacuum pump (which, in the atmosphere, is needed to maintain low pressure within the unit). The instrument is capable of simultaneously monitoring 12 gases, over the range mass 3 to mass 100.

[2] The unit was developed and constructed for NASA by Consolidated Systems Corporation, Pomona, Calif.

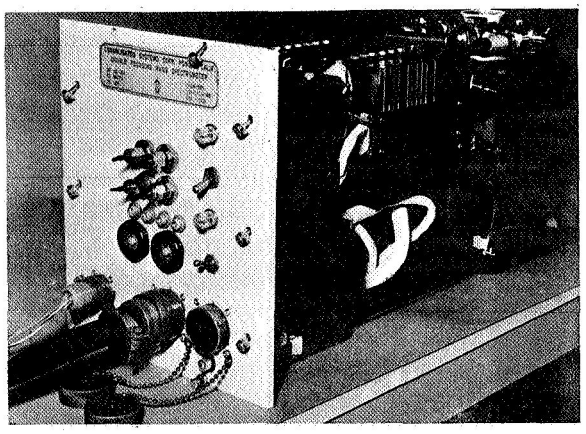

FIGURE 53.—NASA/FRC miniature mass spectrometer.

Figure 53 shows the instrument as delivered to FRC; a simplified block diagram is provided in figure 54. By electrically opening one of the inlet valves, a sample is selected and a gas flow is established from the sample source through the capillary lines, the inlet manifold and the gold leak, to the ion source. The ion pump removes some of the molecules in order to maintain pressure below ambient. An electron beam in the ion source ionizes a small number of the molecules. Under the influence of an electric field, part of the ionized molecules travel out of the ion source through the energy filter into the magnetic sector, the region where they are acted upon by a magnetic field.

The magnetic field is perpendicularly oriented to the velocity vector of the ions and creates a force that acts upon the particles in a direction perpendicular to both their velocity and the applied magnetic field. The resultant movement path is a circle with a radius directly proportional to the particle mass. The ion beam that passes the energy filter consists of ions of all gases in the sample. Upon entering the magnetic sector, the beam is split into the various trajectories with different radii. Collector buckets are located at varying distances, each collecting ions of a different mass. Continuous measurement of the current at each bucket yields the partial pressures of the various gases present.

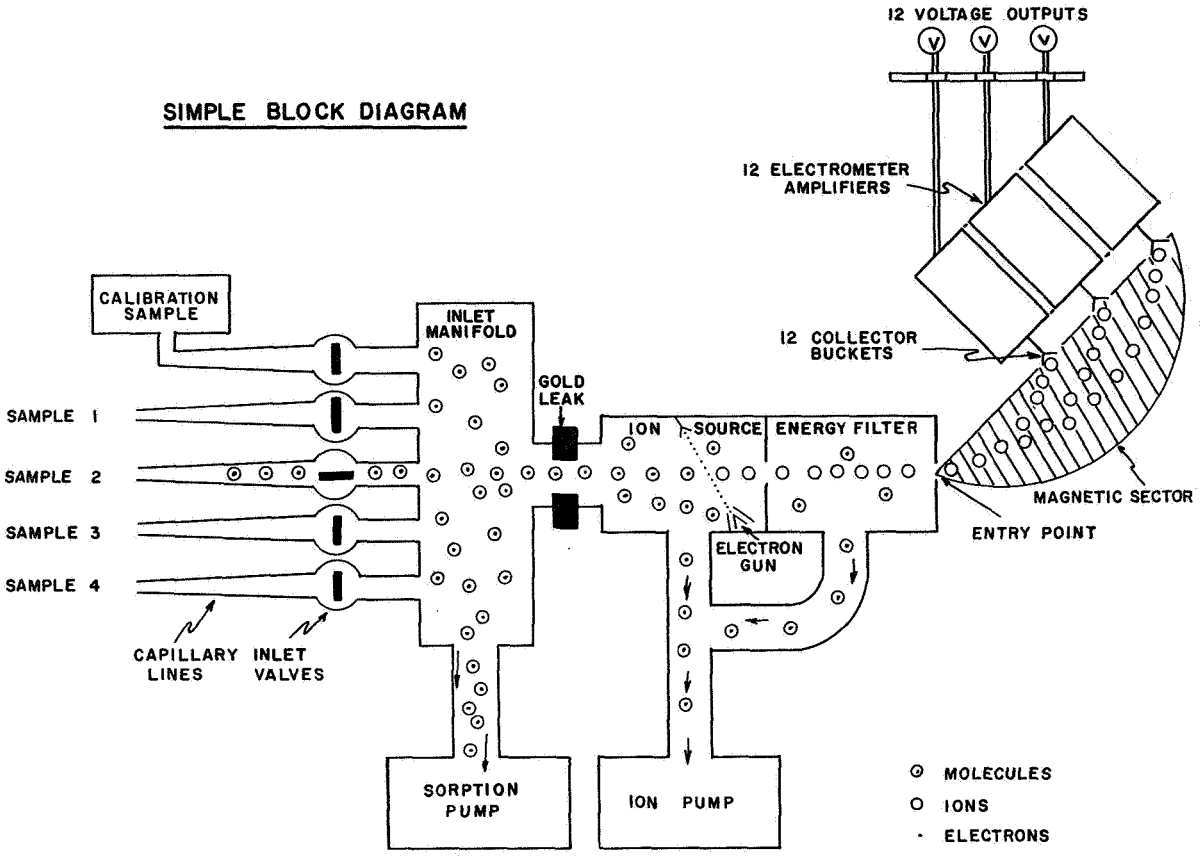

FIGURE 54.—Block diagram of NASA/FRC mass spectrometer.

The double-focusing mass spectrometer was evaluated in a 1-year program at the NASA Flight Research Center (ref. 12). The instrument underwent flight testing as well as ground evaluation for stability of performance, response time, and reliability. In the stability experiments the output of the O_2 channel was plotted continuously at a constant input pressure. Over a 3-hour test period the output remained within ± 2.5 percent of the standard value. The accuracy of the system was ensured by periodic calibration of the entire system against samples of a known gas mixture. (Under operating conditions an automatic calibration is performed every 2 minutes.)

The response time of the instrument was found to vary from 30 to 100 milli seconds depending on channel sensitivity. Response time was determined by injecting a known sample and measuring the time elapsed until the output had reached 99 percent of its final value. The instrument appeared to be reliable and no attention was required in continuous operation, other than replenishment of the liquid nitrogen in the absorption pump. The power requirement of the instrument tested never exceeded 50 watts, with a 28 ± 4 Vdc input voltage. The primary environmental limitation was temperature range, which was found to be $+6°$ C about the ambient temperature. (The magnet was temperature-sensitive over a broader temperature range.) In-flight operation, with maneuvering loads up to 6G and rapid attitude changes, did not alter the performance of the instrument. The original unit is now at FRC undergoing additional tests and refinements.

APPLICATION EVALUATION

The technique of impedance pneumography, greatly refined by NASA, offers a new potential for telemetric recording of respiratory movement and volume. It can be used in a variety of situations where the activity of the subject should not be restricted; and such applications have already begun to appear in the clinical literature. One interesting application of the methods, described by Pallet et al. (ref. 13), is in respiratory recording of newborn babies, where traditional recording techniques adversely restrict the child's activity or increase resistance to breathing. Sargent and Robertson report another clinical application (ref. 14), in which the impedance pneumograph signal is used to trigger an x-ray unit at a specific respiratory phase. The impedance pneumograph also has potential for detecting neurological breathing difficulty in patients under acute stress such as after an operation or cardiovascular accident; it is thus well suited to the needs of intensive care monitoring. Finally, the impedance pneumograph is useful with experimental animals, because even small ones are not constrained by its application. The NASA-developed techniques need little or no modification for nonaerospace applications.

Spray electrodes have a potentially wide application in cases where electrodes are used routinely, for reasonably long periods, or on active subjects. The major advantages are: (1) rapid application, (2) comfort in use, (3) freedom from motion artifacts, (4) durability, and (5) low cost per application. In addition to the aircraft recording situations cited (refs. 8 and 9), the dry electrodes have been used successfully on active children.

The general conclusion drawn from NASA's evaluation was that the double-focusing mass spectrometer shows considerable promise as a practical means of respiratory gas analysis in the inflight environment. The simplicity of operation, accuracy, and stability of this mass spectrometer make it highly suitable, too, for clinical work, particularly where portability is an advantage. Because it is capable of continuous monitoring of the partial pressures of several gases, another application for the device is suggested. The double-focusing mass spectrometer could conceivably add significant quantitative dimension to the clinical practice of anesthesiology, in which monitoring of several anesthetic gases is necessary. In addition, the rapid response time of the mass spectrometer makes it the instrument of choice in determining cardiac output by indirect Fick methods, such as CO_2 rebreathing.

Each of the three NASA contributions described in this chapter is, or will soon be, commercially available. Several bioinstrumentation firms are offering impedance pneumograph units that incorporate NASA-sponsored advances. A commercial version of the NASA-initiated miniaturized mass spectrometer is available. Development and market penetration of the NASA/FRC spray-on electrodes has been undertaken under a separate NASA contract.

Even when current applications are somewhat limited, an outstanding device may well be marketed speculatively to investigators. To some extent, this is now occurring with ultrasonic blood flowmeters and biotelemetry implants, instrumentation whose development NASA has also promoted.

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CHAPTER 8

Spaceflight Bioinstrumentation Fabrication

This chapter describes a number of manufacturing and quality assurance techniques used to meet rigorous environmental stresses without sacrificing size, weight, power, or performance. The discussion focuses on the flight safety system—the sensors, signal conditioners, and wiring harness worn by the astronaut under his spacesuit. Figure 55 shows the components of the Gemini flight safety system. The Apollo system is much the same physically, while in the Mercury system, the signal conditioners were not placed within the spacesuit. Aside from the voice communication gear, the flight safety components provide the primary indication of the astronauts' well-being in space (ref. 1).

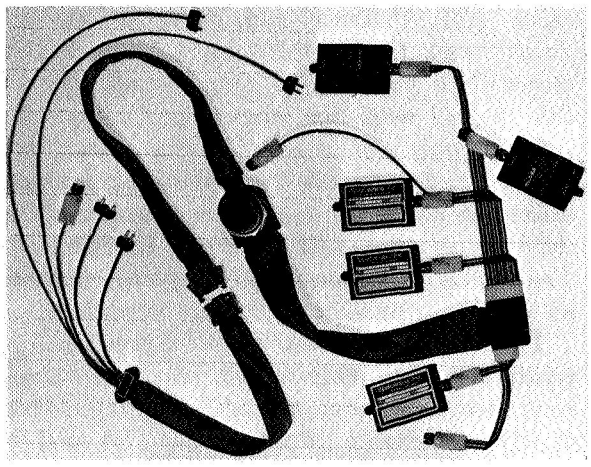


FIGURE 55.—Signal conditioners and connector harness for the Gemini biomedical flight safety system.

For the flight bioinstrumentation, the requirement of minimal failures was reflected in stringent environmental operating specifications, going far beyond those normally associated with medical equipment. The specifications were generated not merely as an exercise in reliability assurance, but in response to the anticipated contingencies of spaceflight. These include vibration, impact, and acceleration stresses at lift-off and reentry, pure oxygen atmosphere, depressurization, high humidity, and temperature in the capsule or close to the astronaut's body, weightlessness, and even the possibility of salt spray or sea water immersion during ocean recovery.

FLIGHT SIGNAL CONDITIONER

From the standpoint of systems design, the flight signal conditioners presented the most difficult fabrication problem. Electronically complex, these units had to be small enough to fit unobtrusively under the spacesuit and rugged enough to withstand the environmental extremes of spaceflight. Moreover, the state of technology at the time the units were designed and manufactured limited them to miniature, discrete electronic components, instead of microminiature integrated circuits of thin film elements.

Accordingly, both the Gemini and Apollo signal conditioners employed welded cordwood construction to achieve high component density and high reliability. In this technique, small electronic components (resistors, capacitors, transistors, etc.) are sandwiched between

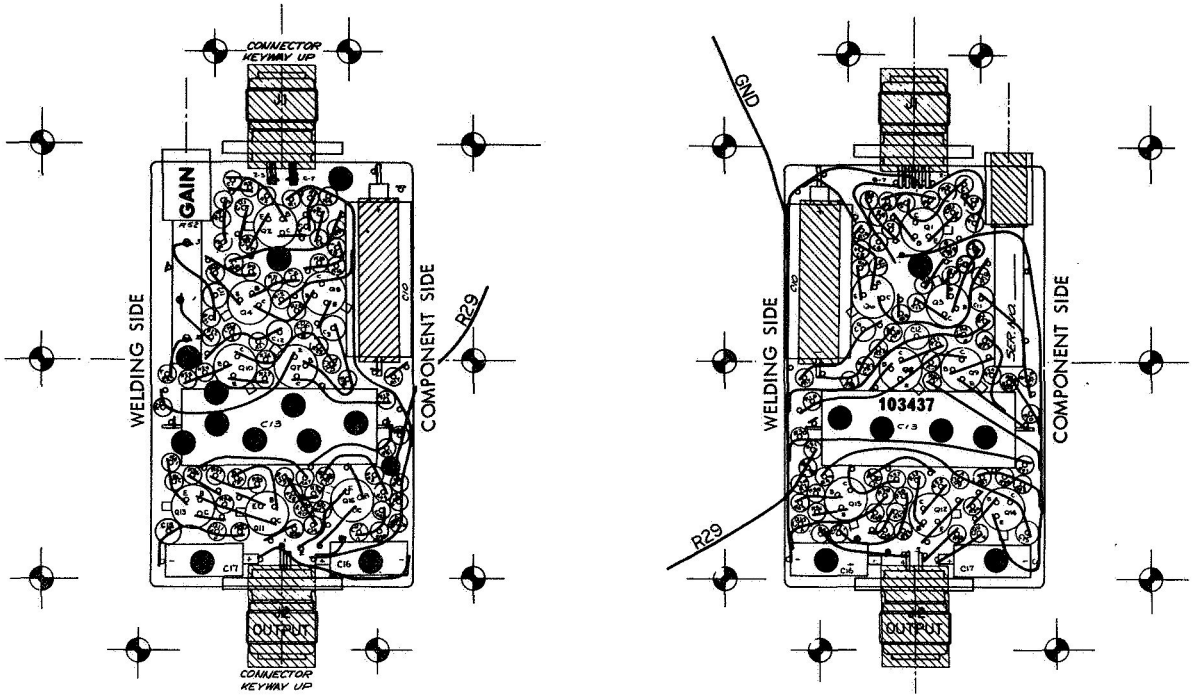


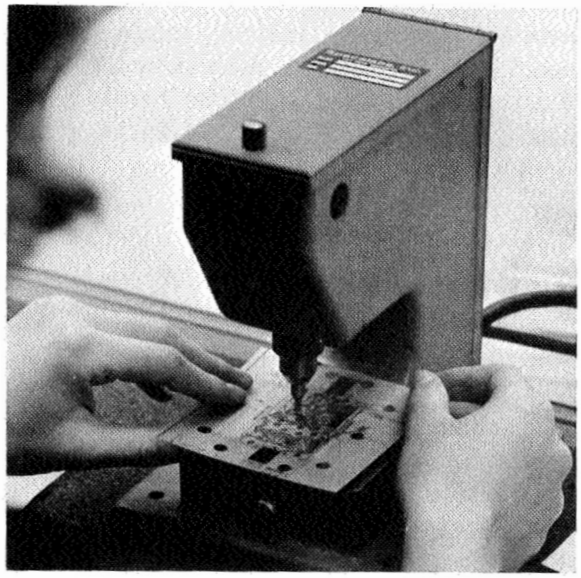
FIGURE 56.—Mylar film template used to position signal conditioner components.

plastic templates. The component leads are brought through the plastic and welded, rather than soldered. When packaged and encapsulated, the resulting units are virtually solid and highly resistant to environmental stress.

The first step in the production of a signal conditioner is the photographic preparation of a set of actual size, transparent, Mylar templates. An example is shown in figure 56. On these templates are printed part locations and the welding ribbon interconnects. The printed wire paths act as guides to the worker, helping eliminate connection assembly errors. Fabrication steps are shown in figure 57. The template is punched (A) to provide holes for inserting the component leads and for positioning it on assembly fixtures. After the "front" and "back" pieces are attached to an assembly fixture, the components are inserted between them (B) in much the same way that a clockmaker assembles the gears of a clock between two brass plates.

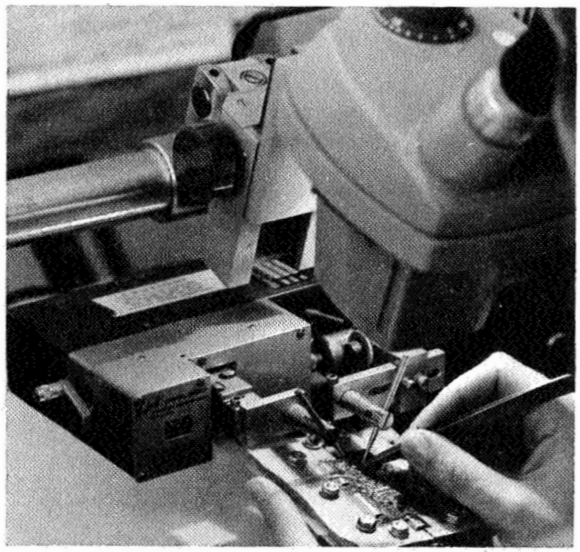
The Mylar sheets are next pushed together, and the two portions of the assembly jig secured. An operator welds the positioned components utilizing a stereoscopic microscope and a special, parallel-gap welding machine (C). Patience and dexterity are required, and the machine must be carefully adjusted to yield an optimum connection. At this point, with the circuit partially completed, specialized or matched components are selected and installed. The completely welded electronic unit (D) is next removed from the welding jig and the Mylar sheets are trimmed. The signal conditioner at this point contains all of its components, including connectors.

The electronic assembly is slipped into a hydro-machined, thin-walled, anodized aluminum case. An opaque, glass-filled epoxy is then slowly introduced into the case (E) and is allowed to solidify under heat. The epoxy provides electrical isolation for the closely packed components and mechanical strength and rigidity for the completed circuit assembly.

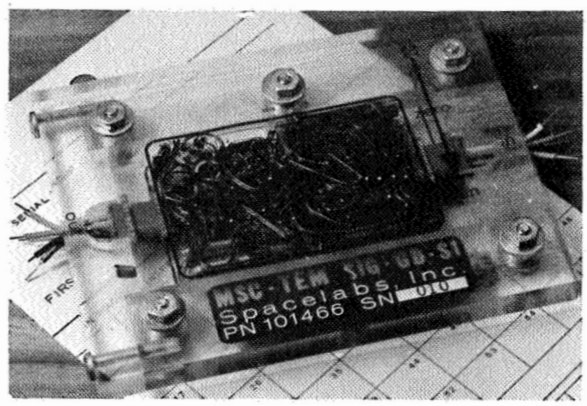


a

b



c



d

FIGURE 57.—Signal conditioner fabrication. (a) punching Mylar film; (b) component installation; (c) parallel gap welding—unit is positioned in a welding jib; (d) welded unit; (e) epoxy encapsulation.

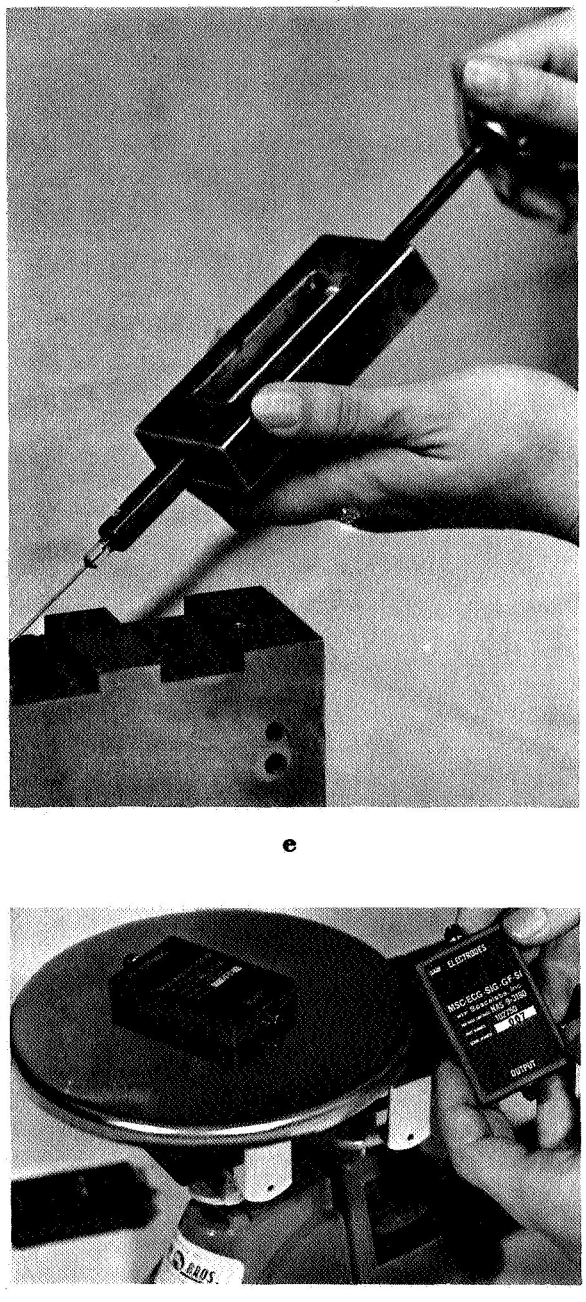


FIGURE 58.—Completed Apollo bioinstrumentation signal conditioner.

The temperature coefficient of expansion of the encapsulating epoxy is matched to the average coefficient of the electronic components so that subsequent thermal exposures of the signal conditioner do not cause internal mechanical stresses. Finally, the nameplate is attached to the case, and the completed signal conditioner is ready for acceptance and qualification testing (fig. 58). The Apollo signal conditioner modules weigh 30 to 50 grams, depending upon type, and occupy about 20 cubic centimeters, or 1.3 inches.

QUALITY ASSURANCE

Spaceflight is the ultimate test of space bioinstrumentation. Yet equipment destined for space must be accepted by NASA on the basis of nondestructive terrestrial examination. To assure that the end items for which it contracted would perform flawlessly, NASA has established an exacting set of quality assurance provisions. These specify quality control procedures for fabrication of the deliverable end items, such as the various signal conditioners, and also provide guidelines for qualification testing. The provisions are stated broadly in NASA quality assurance documents (refs. 2, 3, 4), and specifically in contract work statements. Drawing heavily on previous DOD experience (ref. 5), they are adapted to the unique requirements of spaceflight. For major deliverable items, they ensure close interaction of NASA quality assurance personnel with the contractor's quality assurance, design, and production engineers throughout the development program.

The Apollo flight signal conditioners once again provide an example of procedure. After the design of a specific signal conditioner was fixed, quality control during fabrication depended upon a detailed inspection plan prepared by the contractor and approved by NASA.

ACCEPTANCE TESTING

Each Apollo signal conditioner fabricated was subjected to an extensive series of acceptance tests, that certified its ability to meet key operating specifications. The acceptance tests were conducted in the contractor's facility, for the most part under standard laboratory environmental conditions (an exception was the in-line temperature test).

TABLE 7.—*Typical Electronic Acceptance Test Schedule for the Apollo Signal Conditioner*

Test	Function	Operation time
	Product examination	------
1	Identification	
2	Size	
3	Weight	
4	Connectors	
5	Controls	
6	Workmanship	
7	Finish	
8	Color code	
	Burn-in test	70 hr. 48 min.
9	At 0 hr.	
10	16 through 32 hr.	
11	After 50 hr.	
12	Output dc bias	10 min
13	Input current	10 min
14	Output resistance and parallel operation	10 min
15	Frequency response	10 min
16	Gain	20 min
17	Input impedance	20 min
18	Noise	20 min
19	Recovery time	10 min
20	50-kHz rejection	10 min
21	Common mode rejection	20 min
22	Power input current	10 min
	In-line temperature (−20° C, +70° C)	45 min
23	Initial gain	
24	Gain	
25	Output dc bias	
26	Noise	
27	Common mode rejection	
	Total	74 hr 18 min

Table 7 presents the acceptance test schedule for the Apollo ECG signal conditioner, and figure 59 illustrates the data sheet associated with one particular test. The data sheet records the test results, the test equipment used, and the joint acceptance of the test by quality control personnel from the contractor and from NASA. An acceptance data package about 25 pages long accompanied each delivered signal conditioner. After acceptance by NASA, a historical record is established, which provides a chronological listing for each signal conditioner of acceptance, deposition, tests performed, modifications, and cumulated operating time.

QUALIFICATION TESTING

Two complete Apollo safety bioinstrumentation systems were subjected to flight qualification testing. Flight qualification represents a punishing series of adverse environmental exposures. Its purpose is to validate the basic system design and ensure its operation under

ACCEPTANCE TEST PROCEDURE

3.2.5 INPUT VOLTAGE AND CURRENT AND OUTPUT REGULATION TEST

3.2.5.1 TEST SETUP

3.2.5.2 TEST FUNCTIONS

PARAGRAPH	SWITCH SW1 POS.	INPUT VOLTAGE VOLTS	INPUT CURRENT AMPS	+10 V OUTPUT V TP 3	−10 V OUTPUT V TP 5	QC REQ'MTS
(d)	2					INDICATED
		16.8± .05	.1A MAX.	10± 0.075		REQ'D
(e)	1					INDICATED
		16.8 ± .05	.1A MAX.	10 ± 0.075		REQ'D
(f)	2					INDICATED
		20.8 ± .05	.1A MAX.	10 ± 0.075		REQ'D
(g)	1					INDICATED
		20.8 ± .05	.1A MAX.	10 ± 0.075		REQ'D
(h)	2					INDICATED
		14.8 ± .05	.1A MAX.	10 ± 0.075		REQ'D
(i)	1					INDICATED
		14.8 ± .05	.1A MAX.	10 ± 0.075		REQ'D

ABOVE VALUES WITHIN TOLERANCES ACCEPTED REJECTED

Q.A. STAMPS _____ _____

TEST EQUIPMENT

+16.8 V (a) POWER SUPPLY, H/L 865_____, SERIAL NO.____, CAL. DATE:_____
(b) AMMETER, HP 412A, SERIAL NO.____, CAL. DATE:_____
(c) DIGITAL VOLTMETER, HP 3440A, SERIAL NO.____, CAL. DATE:_____

TOTAL OPERATING TIME_____MINUTES

Q.A. STAMPS _____

FIGURE 59.—Typical acceptance test data sheet.

space conditions. Qualification testing was carried out in the facilities of a subcontractor, following a plan agreed upon, and witnessed by contractor and NASA inspection personnel.

Figure 60 outlines the qualification test sequence for the Apollo flight safety bioinstrumentation system. Systems I and II were identical but traversed different routes in the qualification procedure. The points marked "*F*" on the diagram represent functional tests of the

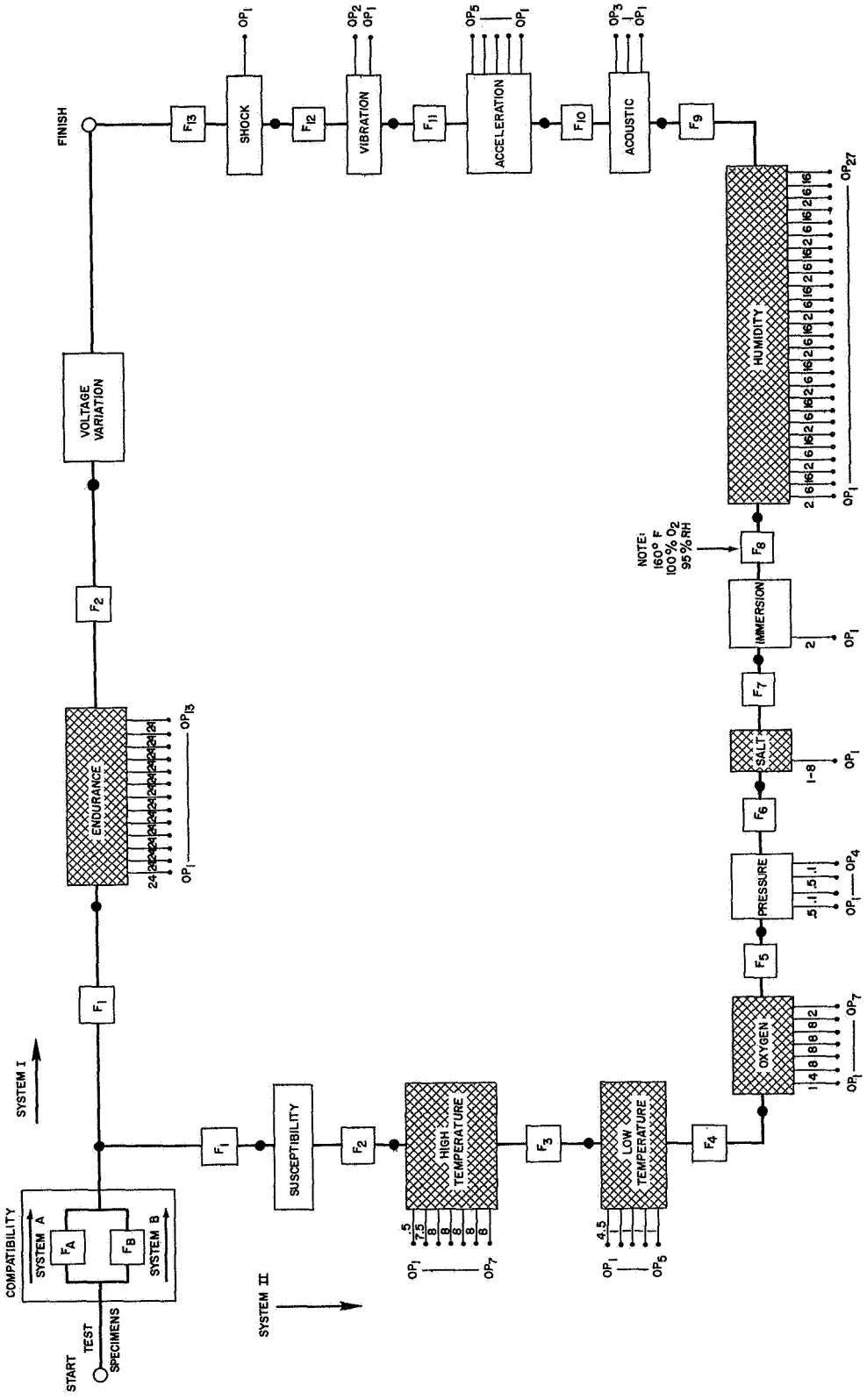


FIGURE 60.—Test sequence for qualification of Apollo flight safety bioinstrumentation.

entire system, undertaken between each individual qualification test; the points marked "*OP*" represent operational tests, undertaken during the qualification test conditions themselves. The functional and operational tests are briefly described below, along with the qualification test conditions.

(1) *Functional test.* The functional test is designed to demonstrate that the system is performing within specified limits. It involves a check of several key parameters for each electronic system component. Table 8 summarizes the measurements made.

(2) *Operational test.* The routine operational test, summarized in table 9, involves an abbreviated set of checks and is made at specified times during each environmental test.

The following represent the qualification test conditions.

(1) *Compatibility.* System components are doubled or interchanged, and functional operation is checked.

(2) *Endurance.* The system is operated at 120° F for 366 hours.

(3) *Voltage variation.* Conducted separately on the different signal conditioners, this test checks the effect of variations in supply voltage.

(4) *Susceptibility.* The system is exposed to conducted and radiated external interference signals in the audio and radio frequency range.

(5) *High temperature.* The system is operated at 160° F for 48 hours, and is checked for electrical performance, physical degradation, generation of toxic gases, or obnoxious odors.

(6) *Low temperature.* The system is exposed to 0° F for 4 hours.

(7) *Oxygen atmosphere.* The system is operated in a 100-percent oxygen atmosphere at ambient pressure and temperature for 40 hours. During the final 2 hours, temperature is increased to 160° F. Checks are made for burning, creation of toxic gases, obnoxious odors, or deterioration of seals.

(8) *Pressure.* The system is operated at 1.0 psia and 160° F for 65 hours. It is checked for crushing, distortion, opening of seals, etc.

(9) *Salt spray.* The system is suspended in a salt spray chamber and sprayed with saline for 48 hours. It is inspected for physical degradation and then functionally tested.

(10) *Immersion.* The energized system with harness connectors attached is immersed in untreated natural human urine for 2 hours. It is de-energized and dried in an atmosphere of 100-percent oxygen, 5 psia, and 160° F. For the next 40 hours, it is alternately sprayed with urine until saturated and allowed to dry without cleaning. Upon completion of the spray-dry cycling, the system is energized and functionally tested in a 100-percent oxygen atmosphere, at 160° F and 95-percent relative humidity.

(11) *Humidity.* In a chamber held at 95-percent humidity, the system is operated at 160° F for 8 hours, then at 100° F for 16 more hours. This is repeated 10 times, giving 240 hours of exposure.

(12) *Acoustic noise.* The system is subjected for 30 minutes to an acoustic source producing an overall sound pressure level of 135 db and a sound frequency distribution peaking between 300 and 600 Hz.

(13) *Acceleration.* The system is subjected to simulated reentry accelerations applied separately along each major axis. The accelerations yield 15.7-G resultants and last 30 seconds.

TABLE 8.—*Functional Test*

Unit	Functional test data
ZPN	Electrode current, supply frequency, output bias, gain
ECG	Output noise, output bias, common mode rejection, gain
Temp & probe	Functional accuracy
dc/dc converter	Regulation

TABLE 9.—*Routine Operational Test*

Unit	Operational test data
ZPN	Gain
ECG	Frequency response
dc/dc converter	Voltage regulation
Harness	Continuity

(14) *Vibration.* The system is subjected to random vibration of 12.6-G RMS, having a power spectral density peaking between 200 and 500 Hz.

(15) *Shock.* The unenergized system is subjected to simulated landing shock (30 G forward and aft, 11 to 15 G lateral) and ultimate shock (40 G forward and aft, 15 to 20 G lateral) lasting about 11 milliseconds. Six impacts are applied, one for each direction along each principal axis.

APPLICATION EVALUATION

To date, no signal conditioner has failed in spaceflight. The exacting manufacture, acceptance, and qualification procedures, however, add to the equipment costs.

TABLE 10—*Production Operations for Apollo ECG Signal Conditioner*

Activity	Number
Parts (100% inspection)	121
Secondary operations	23
Assembly operations	31
Welds	422
Manufacturing inspections	33
In-line functional tests	9
In-line special tests	7
Finishing operations	6
Acceptance test operations	87
Total	739

Table 10 summarizes the major operations required to produce an Apollo ECG signal conditioner (ref. 6). About 100 manhours are associated with the 739 activities. Of the 739 activities, 57 percent are welding operations, and about 35 percent are inspection and testing. Inspection and testing are time consuming, so the 35 percent figure probably represents a substantially greater portion of the 100 manhours.

NASA's requirements for inspection testing and record keeping, particularly for component parts, are exceptional. Most likely they could be relaxed somewhat for nonaerospace applications at a considerable cost saving, without significantly reducing unit reliability. Further savings would be provided by volume production, since much of NASA's expense covers initial development efforts. But even if unit cost was lowered, bioinstrumentation of comparable performance and ruggedness would always remain relatively expensive.

Are there nonaerospace applications for the type of instrumentation engendered by spaceflight? It appears that there are. One application has developed in another realm of exploration—undersea habitation. Because nitrogen is narcotic at great pressures, undersea facilities, such as the U. S. Navy's Sealab I and II, require a helium atmosphere. Helium is a light gas, easily permeating otherwise sealed electronic units. At high pressures such an atmosphere is destructive to much standard electronic gear, making it difficult for scientific investigation, particularly physiological monitoring, to be conducted underwater. Recently, a standard Gemini signal conditioner was tested in a simulated undersea environment to examine the general sturdiness of its design. Although originally designed to operate at a near vacuum in 100-percent oxygen, the unit performed perfectly at 200 psig in 100-percent helium for several hours. A pressure of 200 psig is equivalent to a depth of 430 feet, the planned level of the Sealab III habitation project.

There are also other practical monitoring tasks for which the size, weight, power and reliability requirements placed on space equipment represent realistic system specifications. It has been proposed that helicopter rescue be initiated for the victims of highway accidents. Plans under consideration involve an instrumented, telemetering "stretcher" that would enable the central hospital emergency room to monitor a patient from the time he is contacted, while he is being transported, and during any necessary medical treatment. The elements of such a system are closely analogous to those of the space monitoring network; and the environmental contingencies of mechanical shock, temperature extremes, and salt spray are also much the same.

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CHAPTER 9

Conclusions: Application of NASA Contributions

The major aim of this survey has been to promote the application of NASA bioinstrumentation contributions to nonaerospace medicine and industry. The preceding chapters have described a large number of contributions, selected from the many available, and have presented them in the framework of bioinstrumentation system development. Additional citations and references have been supplied to lead the reader into the larger body of NASA's work in the field.[1]

There appear to be three main avenues by which the objective of this report may be fulfilled; these are:

(1) *Primary transfer.* A NASA technique or device is applied unchanged to a nonaerospace situation.

(2) *Secondary transfer.* A NASA technique or device immediately suggests a secondary development program, which leads to a technological modification or extension for the nonaerospace situation.

(3) *Technical infusion.* Examination and discussion of NASA's design approach and methodology promotes a heightened understanding of biomedical engineering problems, facilitating the subsequent manufacture and utilization of advanced bioinstrumentation in nonaerospace areas.

Suggestions for primary and secondary transfer have been presented throughout the survey, along with some examples of devices and techniques which have already made the transition. Every current bioinstrumentation trade magazine carries advertisements for numerous commercial variants of NASA-originated and NASA-sponsored devices. The importance of this type of transfer cannot be overemphasized, but to a large extent it depends upon the participation of specialists working within their areas of competence.

Technical infusion, on the other hand, generally depends on personnel crossing lines of specialization: the engineer considering the needs of medicine; the doctor applying techniques of engineering design and analysis, as well as employing engineering products. It is apparent today that a new cooperation is being established between the technological disciplines and the field of medicine. Evidence of this is seen in the journals devoted to research and development in this field; for example: (1) The IEEE Transactions on Bio-Medical Engineering, (2) Medical & Biological Engineering (formerly Medical Electronics and Biological Engineering; the Journal of the International Federation for Medical and Biological Engineering), and (3) Medical Research Engineering (formerly the American Journal of Medical Electronics). Further evidence is found in the proliferation of trade magazines, symposia, and university curricula devoted to the engineering-medical interaction.

It is also apparent that while NASA cannot claim sole responsibility, it has provided much impetus for these promising interdisciplinary efforts. NASA has accomplished this by using

[1] A discussion of the medical market with reference to specific NASA innovations can be found in reference 1. The general question of applying space technology to medicine is treated by Hartwig (ref. 2) and Hartwig and Bendersky (ref. 3).

medical personnel in the front line of complex technological planning and by closely involving the aerospace industry in advanced bioinstrumentation programs. A climate of appreciation has been established which yields a self-perpetuating "delayed fallout" of innovation and improvement.

For example, the senior author recently visited a major aerospace research and development firm. A design engineer there had developed a compact and lightweight pneumatic pump for a specific space application. He had considered other potential uses of the device and had decided that it showed promise as an implanted heart-assist pump. Soon, a small research study was underway to test the feasibility of this application. The firm had participated previously in NASA-sponsored bioinstrumentation studies; its engineers were used to thinking of medicine and engineering as interrelated. Consequently, medical extension of an engineering solution was natural, where it might not have otherwise been. One can anticipate a great multiplication of such examples in the future.

The point here is that while several specific NASA contributions to bioinstrumentation may reappear rapidly in nonaerospace use, the most significant effects of the NASA development programs may be more diffuse. While the authors will be gratified if this survey aids designers or planners in the immediate transfer of aerospace technology, they will be equally pleased if it enhances the climate of interdisciplinary cooperation and appreciation which in the future will make possible even greater advances.

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Glossary

acquisition, telemetry—interval of telemetry signal reception, e.g., from a spaceship.

amplitude modulation (AM)—combining a signal with a carrier wave such that the carrier's amplitude varies in accordance with the amplitude of the signal.

analog—signals involving continuous variables.

artifact—unwanted, spurious, stray, or random noise appearing in an electrical network.

bandwidth—a continuous sequence of frequencies; the extent of the sequence.

bioelectric—electrical phenomena of, or associated with, living organisms.

bioinstrumentation—devices associated with the measurement of physiological effects in living organisms.

biotelemetry—pertaining to the transmission of physiological information over distance.

cardiotachometer—device for calculation and recording of the heart rate.

cardiovascular—pertaining to the heart, veins, arteries, capillaries, and the functions thereof.

decibel (db)—a logarithmic unit for measuring any signal intensity; used as a measure of response in electrical communication circuits.

demodulator—a device that extracts the original signal from the modulated carrier.

differential amplifier—a device that amplifies the potential difference between two active inputs, referenced to a third.

digital—signals, calculations, or displays involving discrete units.

discriminator—the portion of an FM circuit that changes frequency modulation to amplitude modulation.

electroencephalogram (EEG)—a record of electrical brain waves made by an electroencephalograph.

electroencephalograph—a device with leads to the scalp which records the electrical currents occurring in the cerebral cortex.

electrocardiogram (ECG or EKG)—a tracing of the heart's action currents; used to determine abnormalities in the heart.

electrocardiograph—an instrument for recording changes in potential in the electrical currents which traverse the heart and initiate its contraction.

ECG complex—referring to the periodic set of waves in the electrocardiogram; the individual waves are identified as *P*, *Q*, *R*, *S*, and *T*. The *QRS* complex is often separately specified.

electrolyte—a nonmetallic electric conductor in which current is carried by the movement of ions; a substance that when dissolved in a suitable solvent, or when fused, becomes an ionic conductor.

frequency—the number of times that a function repeats during a unit time interval.

frequency modulation (FM)—modulation of the frequency of a carrier wave in accordance with the amplitude of the input signal.

frequency response—the band of frequencies a circuit will pass, or is sensitive to.

gain—value representing the ratio of the increase in the output voltage of an amplifier to the change in input voltage.

hard copy—printed information, in contrast to oscilloscope presentation.

Hertz (Hz)—unit designation for frequency. One Hertz is defined as one cycle per second.

impedance—inherent resistance experienced by alternating current in an electrical circuit. Mathematically, it has a real and imaginary portion.

integrated circuit—several electronic components integrally part of the same substrate, generally quite small.

multiplex—a technique by which several discrete electrical signals are transmitted on the same circuit.

noise—any unwanted signal in an electronic circuit.

on line—used during the actual operation, as on-line data processing.

oscillator—a circuit that produces audio or radio signals at specific frequencies.

phonocardiogram—a record of heart sounds made by means of a phonocardiograph.

phonovibrocardiogram—a phonocardiogram extending into the very low (vibration) frequency regions.

pneumotachometer—a device for recording the speed of air flow with respect to time; also, a device for recording breathing rate.

qualification—demonstration of equipment ability to meet specified environmental stresses.

R-wave (also see **ECG complex**)—the first positive deflection of the *QRS* complex in the ECG.

respiration tachometer (see **pneumotachometer**)

root mean square (RMS)—a measure of average signal strength.

signal—a detectable physical quantity or impulse by which information may be transmitted.

signal-to-noise ratio—the ratio of desired to undesired information.

solid state—electronic circuitry contained on or within a semiconducting material such as silicon, gallium or germanium. A transistor is a solid-state element.

specifications—technical parameters governing design, fabrication, or performance of equipment.

telemetry—process by which information is obtained and transmitted, usually by radio, to a distant receiver.

thermistor—a resistor made of a material whose resistance varies in a known manner with temperature.

time line—a chart or diagram presenting a series of events in their progressive order.

vectorcardiogram—a graphic representation of the magnitude and direction of the heart's action potential; three-dimensional ECG.

weightlessness—zero gravity or freefall.

ZPN—impedance pneumograph.

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