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CHAPTER 3
BIOINSTRUMENTATION

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Introduction

With the inception of the United States space program, continuous monitoring of vital signs was a relatively new concept. Since that time, the technology of biotelemetry – long distance transmission of physiological information – has come of age. Thousands of hours of data have been transmitted from space to the Earth from as far as 400 000 km (250 000 miles) away. Only when astronauts were in lunar orbit on the far side of the moon was there an interruption in the steady transmission of vital sign data to Earth-based physicians and mission controllers. All three crewmen were continuously monitored during Apollo missions 7 through 13. Beginning with Apollo 14, data were obtained on a continuous basis for at least one crewman. Both the Commander and the Lunar Module Pilot were closely monitored during the performance of lunar surface extravehicular activities, but because only one channel was available in the Lunar Module data were collected for only one crewman.

It was essential that vital signs be monitored during space flight. During early space flight operations, there was uncertainty as to the effects of space flight factors on normal physiological functioning. Transmission of physiological data provided essential information upon which a decision to abort a mission could have been reliably made from the ground, should it have become necessary. During Gemini missions, astronauts operated for the first time in the new environment of free space during the performance of extravehicular tasks. Vital sign monitoring coupled with voice communication in this instance dictated that early free space EVA be cut short because these activities proved too taxing. Later, modifications of training and procedures enabled astronauts to perform long-term extravehicular activities safely.

During Apollo missions, all three crewmen were instrumented for medical monitoring during operation in the Command Module, the Lunar Module, and during extravehicular activity in free space and on the lunar surface. Lunar surface activity imposed stresses of an unpredictable nature on the lunar surface crewmen. While attempts to simulate lunar walking and operating conditions were made during ground testing, the full nature of the effect of the lunar terrain on work efficiency and, hence metabolic rate, was not known until the first lunar surface mission. Medical monitoring during these operations permitted real-time adjustments in activity timelines formulated before flight as such alterations were needed. Such data permitted changes in the scheduling of Apollo 15 lunar surface tasks when electrocardiographic recordings and other data indicated that this crew was being subjected to excessive workloads.

The Apollo bioinstrumentation system (BIS) requirements evolved as a continuation and refinement of medical monitoring systems utilized throughout the Mercury and Gemini Programs. The BIS and related hardware provided physiological data to ground-based medical personnel for operational inflight safety monitoring; for inflight medical experiments; and for ground-based operations safety monitoring.

System Description

The Apollo BIS had two configurations. The early Apollo (Block I) Program was terminated prior to any actual space flights. All missions from Apollo 7 through Apollo 17 (Block II) utilized the BIS.

The system planned for Block I of the Apollo Program consisted of two electrocardiographs (ECG), one impedance pneumograph (ZPN), one body temperature signal conditioner, a DC to DC converter, and appropriate electrode, temperature probe, and interconnecting cables (see figure 1). The Block I configuration was designed, fabricated, and qualified for flight use, and was utilized in Block I ground tests until the spacecraft 204 accident. The design and packaging concepts were essentially the same as developed for Gemini, except for the addition of the DC to DC converter, providing a high level (0 to 5 VDC) output signals to the spacecraft telemetry system. The body temperature measuring components (figure 2) were added for ground tests only, and were not included in the flight configuration.

The Block II (figure 3) system utilized the same components as did the Block I. The only system difference was the deletion of one of the ECG measurements. The temperature measurement capability was again provided for ground testing. Block II signal conditioners differed only in their grounding configuration. Block I units had a common connection for case ground and signal-power ground, while Block II utilized separate connections for improved radio-frequency interference characteristics. Block I and II units were, otherwise, electrically and physically identical.

The Apollo signal conditioners were designed to be of uniform size, 5.84 cm x 3.81 cm x 1.04 cm (2.3 in. x 1.5 in. x 0.41 in.), with identical miniature input and output connectors. Color coding was incorporated to facilitate proper mating with their respective connectors on the bioharness and electrode harnesses.

Electrocardiogram Signal Conditioner

The ECG signal conditioner and electrodes were designed to provide inflight measurements of a crewmember's ECG activity and to develop a signal wave ranging between 0 and 5 volts peak-to-peak, which is representative of crewman ECG activity. The unit was provided with an adjustment that permitted preflight calibrations. The electrical activity sensed by the body electrode was passed into the signal conditioner which had an input impedance of greater than 40 megohms, and common mode rejection greater than 100 000 to 1. The gain of the signal conditioners was continuously variable from 600 to 4500, and the output was the amplified ECG waveform which varied ±2.5 volts about a 2.5-V bias. Harmonic distortion was less than 1.0 percent over the unit's frequency bandpass of 0.2 Hz to 100 Hz. Signal conditioner power of plus and minus 10 VDC at .5 milliamperes was required from the DC to DC converter.

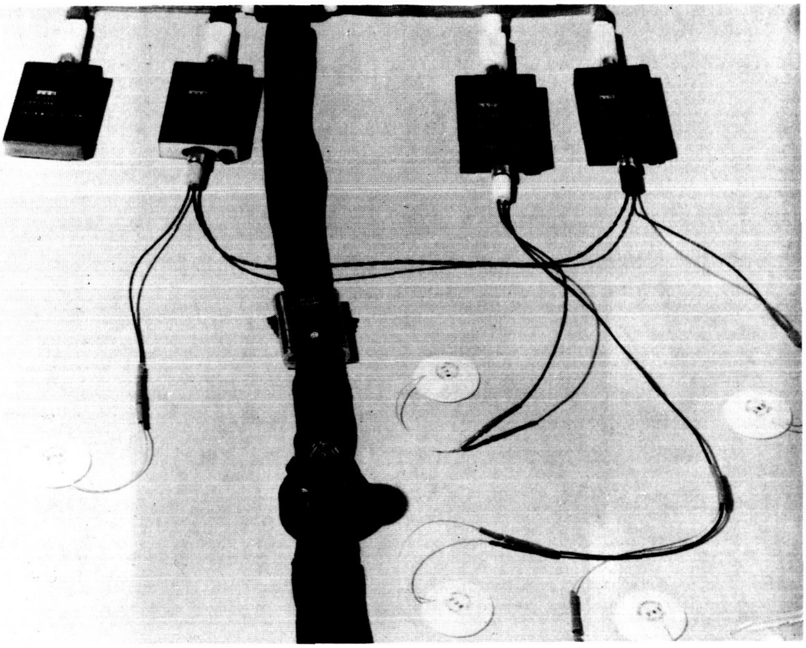

Figure 1. Apollo Block I configuration of bioinstrumentation system.

Impedance Pneumograph Signal Conditioner

The ZPN signal conditioner and electrodes were designed for measurement of a change in the transthoracic impedance to a low level current at a frequency of approximately 50 kHz. Measurement was obtained from a pair of electrodes that developed signals (0 to 5 volts peak-to-peak) corresponding to the respiration rate over a wide dynamic range of respiratory activity. The excitation circuit accommodated electrode impedance of 100 to 1000 ohms, and the signal conditioner input impedance was greater than 1 megohm at 50 kHz and greater than 60 megohms in the 0 to 100 Hz frequency range. The output had a range of 0 to 5 VDC with the respiration signal varying about a 2.5-V bias level. Power drain from the DC to DC converter plus and minus 10-V supply was less than 7 milliamps. This unit was also provided with adjustments to accommodate the characteristics of the individual.

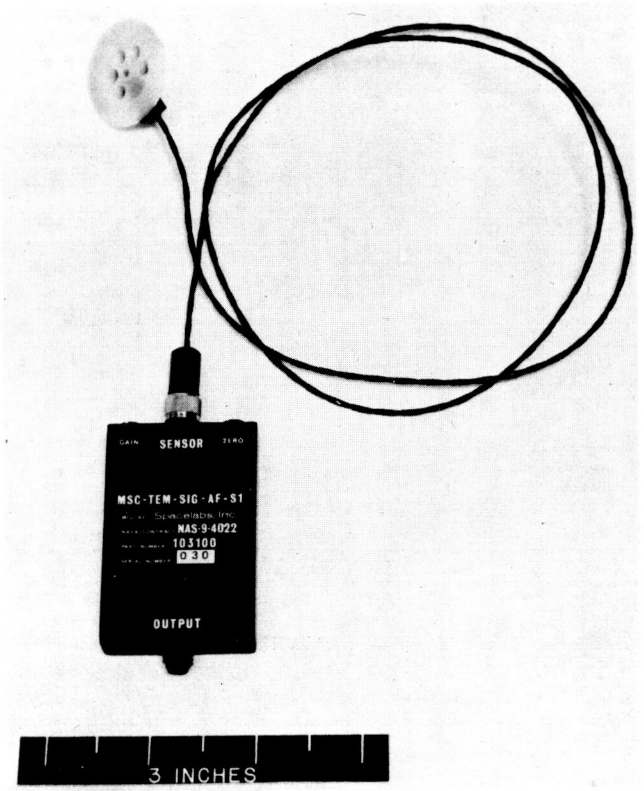

Figure 2. Body temperature measurement system.

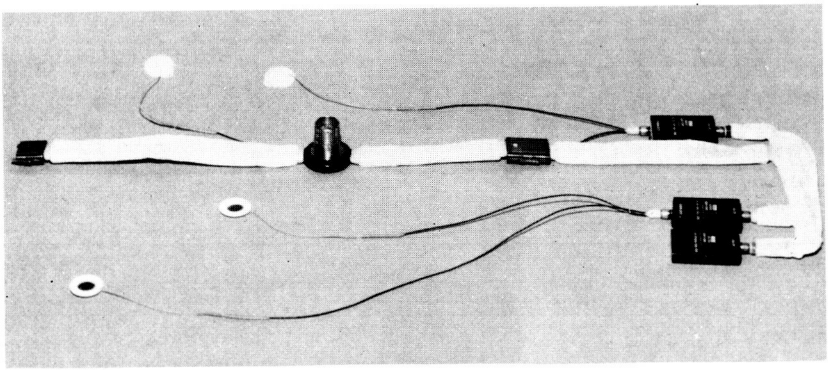

Figure 3. Apollo Block II configuration of bioinstrumentation system.

Body Temperature System

The body temperature probe and signal conditioner produced an output voltage in the range of 0 to 5 VDC corresponding to sensed temperatures of from 303° to 319°K (85° to 115°F). The system accuracy was within ±0.17°K (±0.3°F) and had a response time to a 2.8°K (5°F) step change of five seconds. Power requirements were less than 5 milliamps from each of the DC to DC converter supply voltages.

DC to DC Converter (DCC)

The DCC as designed and delivered for Apollo provided isolated, balanced plus and minus 10-V outputs. The outputs were regulated within ±0.1 volt over a current load range of 0 to 30 milliamperes drawn from either side and with an input voltage of between 14.8 and 20 VDC. Output impedance was approximately 3 ohms and output voltage ripple less than 1 mv peak-to-peak.

Investigation into the potential short circuit fire hazards inside the space suit revealed that, by shorting the output leads of the DC to DC converter, a spark could be produced which would ignite cotton in the presence of oxygen under conditions of 131 kN/m^2 (19 psia). This ignition source was traced to output capacitor energy storage in the DC to DC power converter and to the ability of the output capacitors to produce a high-current pulse in a short-circuit condition (even though the output current would go to 50 milliamperes in a steady-state condition). The high-current pulse and the associated ignition hazard were eliminated by installing resistors that limited the current in the positive 10- and negative 10-volt output leads of the DCC.

The incorporation of these resistors influenced performance of the DCC due to the increase in effective dynamic output impedance since the resistors could not be placed in the voltage regulation loop. Output impedance, therefore, increased by 10 ohms and the regulation increased from ±0.1 VDC to +0.1 VDC, -0.4 VDC under load variations.

Electrode Harnesses

The sternal-electrode harness was a small cable used in conjunction with the ECG signal conditioner. The harness provided the electrical interface between the crewman's electrode and the ECG signal conditioner. The cable also contained the system ground electrode, which was a high-impedance ground primarily used to remove the static charge from the crewman.

The axillary-electrode harness was a small cable used in conjunction with the ZPN signal conditioner. The cable provided the electrical interface between the crewman's electrodes and the ZPN signal conditioner. Both electrode harnesses originally utilized silver/silver chloride anodized discs in an acrylic housing. The wiring to the connector which mated to the signal conditioner was Teflon insulated, and incorporated miniature pin jack connectors in-line for quick-disconnect capability.

Several changes were made to the harnesses during the Apollo Program as a result of inflight problems, testing, and operational changes. During the first manned Apollo mission, data were lost due to separation of the pin jack connections inside the space suit and also to wire breakage at the connectors. Therefore, the electrode harnesses were redesigned to eliminate the pin jack and the electrodes were wired as a permanent part of the harness (figure 4). Also, the wire was changed from Teflon insulated to polyvinyl chloride (PVC) insulated and a soft silicone rubber strain relief was added to the connector. This eliminated the problems on all subsequent Apollo missions.

Continued testing during the program revealed a sneak ground path in the input circuit of the ECG signal conditioner (which provided a current path to ground if the crewmen should contact a voltage source). The solution to this problem required increasing the input lead impedances by adding series current-limiting resistors to the sternal-electrode harness. Also, a ground electrode with a series resistor was added to reduce noise and artifact in the ECG data.

For missions through Apollo 14, the electrodes were filled with electrode paste and attached to the crewman by double-back adhesive tape. Figure 5 shows a subject wearing the biobelt with the electrodes in place. The electrodes were then covered with porous surgical tape that permitted normal skin respiration. The electrochemical activity that occurs at the electrode surface was degraded when the anodizing was damaged. This problem occurs after many use cycles. Therefore, when it was decided that, for Apollo 15 and subsequent missions, the crewmen would be permitted to remove and replace their electrodes during flight, the integrity of the anodized disc was doubtful. This problem was eliminated by replacing the disc with a pressed pellet made of powdered silver/silver chloride. This technique provided a homogeneous electrode that was not affected by small surface damage.

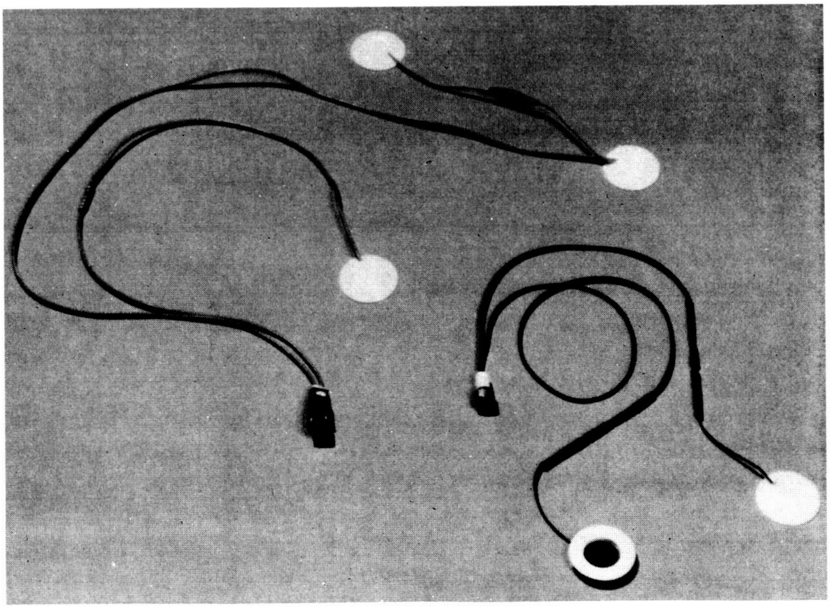

Figure 4. Apollo sternal-electrode harness and axillary-electrode harness.

Crew Interface

The bioinstrumentation system, which was required both in the vehicle and during EVA, was designed to be worn inside the space suit. The biobelt containing the instrumentation (figure 6) provided a compact means for placement and stowage of the signal conditioners and the DC to DC converter. Snap fasteners were used to mate the biobelt to the midriff section of either the constant wear garment or the liquid cooling garment. The signal conditioners and the DC to DC converter were available for easy connection to the biomedical harness and the sensing equipment. Elastic straps were used to maintain the contents in a fixed position, and an overflap snapped over the contents of each pocket. The overflaps were fabricated of Teflon-coated Beta cloth to satisfy flammability requirements.

The electrode attachment technique was designed to maintain long-term reliable body contact for good signals, but attachment was difficult to maintain without discomfort and skin damage. Because electrodes became dislodged under such severe efforts as suit doffing and donning, a kit was provided with attachment materials to replace electrodes during unsuited periods.

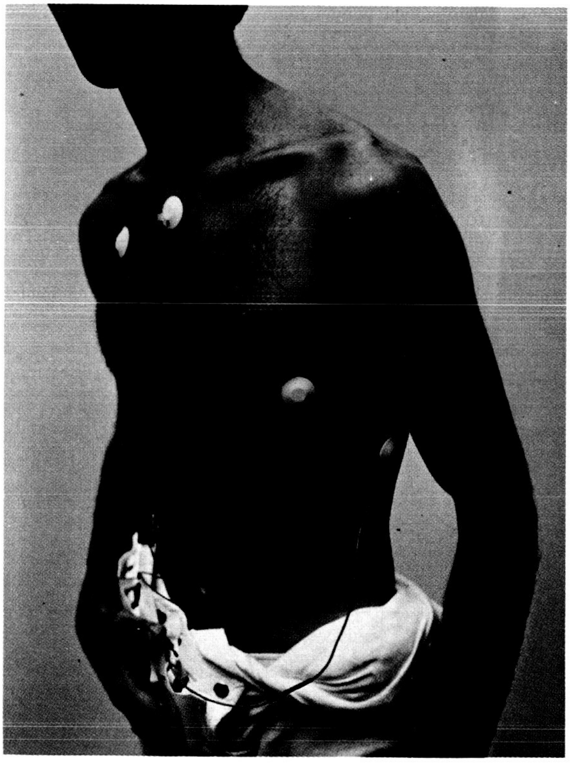

Figure 5. Biobelt being worn with electrodes in place.

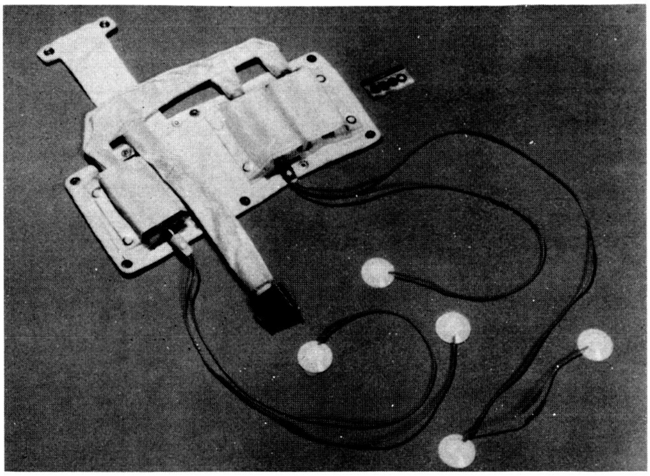

Figure 6. Bioinstrumentation system in the biobelt.

Results and Discussion

The bioinstrumentation system provided essential data in support of Apollo missions. With the incorporation of current limiting modifications, the electronic system proved to be very reliable. As expected, electrode attachment was a recurring, but minor, problem which required crewmembers to reattach the displaced electrodes.

Figure 7 represents a typical ECG signal received at the Mission Control Center during various periods of the Apollo 11 mission. Figure 8 shows electrocardiographic tracings

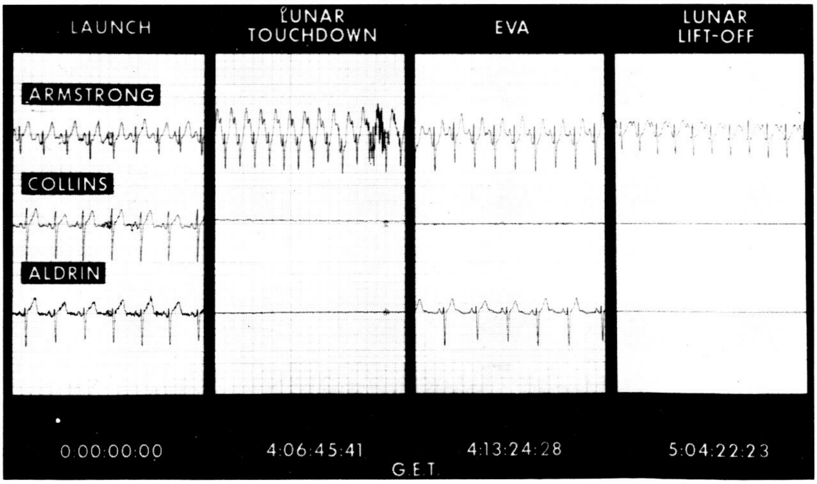

Figure 7. Typical ECG signal received during Apollo 11 mission.

obtained during the Apollo 15 mission during periods of cardiac arrhythmia. These data led to a reassessment of workload and diet for subsequent crews, and alterations in onboard medical supplies to include antiarrhythmic drugs.

This chapter has treated bioinstrumentation from its engineering aspects. The reader is referred to Section II, Chapter 1, for clinical aspects of medical monitoring and the bioinstrumentation system.

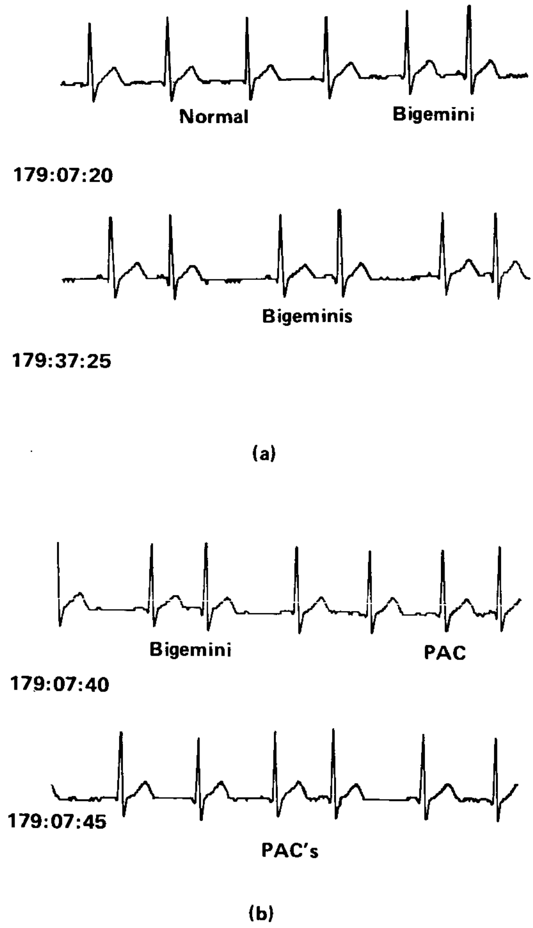

Figure 8. Apollo 15 ECG tracings obtained during periods of cardiac arrhythmia. (a) shows the normal heart beat converting to a nodal bigemini rhythm; (b) shows the bigemini rhythm converting to premature auricular contractions.