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CHALLENGES OF PHYSIOLOGICAL MONITORING
IN A NAVY OPERATIONAL SETTING

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The requirements to evaluate naval personnel performance and the challenges of quantifying the physiological requirements of varied work tasks are inherent in all naval communities (diving, marine amphibious assault, special warfare, surface, sub-surface, and flight). The objectives of such requirements include not only safety but the development of selection and performance standards to better conserve personnel and maintain combat readiness in the Navy.

The effect of naval operations with a mix of multiple interactive stressors, e.g., extended operations, G-loading, thermal loads, motion/disorientation, multi-cognitive tasks, hypo/hyperbaric exposure, etc., as well as disease and injury potential, requires the development of critical field usable assessment techniques. Data that can be obtained from such techniques in the varied operational settings form the basis for simulation of adverse field environments in the laboratory where medical capability (selection/retention) criteria, mission modeling, man-machine interface design, and performance enhancement techniques can be developed, studied, and eventually fleet implemented. Examples of current Navy R&D thrusts in field physiological monitoring include: (a) performance assessment of Navy divers and combat swimmers during extended water exposure, (b) event related potential (ERP) monitoring of surface ship and submarine sonar operators, (c) in-flight assessment of fatigue indices in the anti-submarine warfare community and (d) quantification of cardiac stress in fighter pilots during air-to-air combat maneuvers.

DIVING

The U. S. Navy diving community is principally composed of three types of divers: (1) the traditional "Hard Hat Diver" who is responsible for diving to great depth for such missions as ship salvage, (2) the Explosive Ordnance Diver/Swimmer who is principally a shallow water diver responsible for placement/removing/disposing of ordnance in areas such as harbors, beach assault fronts, etc. and (3) the Naval Special Warfare operator (better known as a Sea/Air/Land (SEAL) Special Commando or Frogman) who in addition to many land base commando responsibilities is responsible for shallow water diving/swimming that may require greater than 6 hours of continuous immersion in varied temperature waters.

In order for mission accomplishment (peace time as well as combat) varied physiological/psychological concerns are presented for the Navy diver: decompression sickness, fatigue, cardiac stress, equipment malfunction, and the most prevalent, hypothermia, each of which leads to performance decrement and a threat to life. Reasoning for physiological monitoring for the sake of identifying such decrement/occurrences are twofold, (1) as a means for team/individual warning signals for completion/termination of mission or for implementation of protection techniques and (2) as an R&D effort to better understand the physiological requirements and responses of diving operations so that improved enhancement techniques can be developed.

A recent diving R&D effort was conducted to evaluate diver thermal status and performance during cold water immersion wearing dry or wet suits. Activity level, diet, time of day for the dive, and water temperatures were varied. Core and skin temperature responses and heat flux-data were collected (Fig 1). The data acquisition system as described by Weinberg (Ref 1) included skin and rectal temperature transducers with a constant current Wheatstone bridge circuit located near the computer to convert the changes in thermistor resistance into voltage levels. This provided a high S/N* ratio in the electrically noisy hyperbaric chamber environment and allowed simple computer sampling. Heat flux was converted to a multivolt level signal by a sensor disc that contained integrally the thermistor. Thermal data obtained are being used to validate several models of diver thermoregulation to produce safe exposure, guidelines, and selection charts for thermal protection garments.

In 1976 a National Plan (Ref (2)) was published which addressed concern for diver safety and performance decrements and the importance of varied monitoring techniques in the operational setting. These techniques included voice communications, heart rate, and respiratory and thermal parameters. A 1978 workshop (Ref (3)) supported these issues and developed the following conclusions regarding physiological monitoring of the diver.

- a. The importance of visual monitoring
- b. That monitoring suffers from lack of adequate sensors
- c. A majority of the difficulty is in interpreting what is monitored
- d. There is a need to assess physiological response against time
- e. There is a need to reference physiological variables against individual physiological profiles
- f. There is a need for real time display of physiological variables for supervisor use.

*S/N (signal-to-noise ratio).

These conclusions have not changed dramatically since 1978.

Outside of a controlled laboratory setting, operational feasibility is the major limiting factor for good physiological monitoring in a diving setting. Whether data transfer is by cable or telemetry or pier/ship side monitoring equipment, diver "Jury/Rigging" is the norm (Figs (2) & (3)). Use of physiological sensors are continually difficult due to environmental exposure, time required for attachment, acceptance for use (e.g., rectal thermometer) data transfer interference, and quick data interpretation (especially for the individual diver). As addressed in (Reference (3)), the "ideal" diver operational monitoring system is a system that will monitor physiological and environmental parameters by sensors built into the diving suit and equipment, with real time digital readout, error-free data link to a monitoring point capable of immediate analysis, comparison with the individual diving profile, and prediction of outcome.

ELECTROPHYSIOLOGICAL MONITORING

Navy sonar operators are common to both surface and subsurface ships. Their tasks mandate a continued vigilance on sonar screens for any indication of nearby vessels. The nature of this job includes extensive information processing, frequent dual tasks, and a requirement for unobstructed attention and performance for sustained periods of time. We know that the human information processing system is limited in its capacity to handle multiple inputs and is subject to diverted attention and fatigue even in the best of trained operators. In a naval combat environment such deviation could prove disastrous. A current hypothesis is that decrements in neuroelectrophysiological components, which have been found to be highly correlated to attentional mechanisms (Ref (4)), can be detected prior to the onset of actual performance decrement. This theory provides a potential for R&D laboratory assessment and development of a performance monitoring tool for shipboard use. In a laboratory setting collection of neuroelectric responses during varied simulated tasks can be utilized to determine several possible performance counter-degradation techniques e.g., improved sleep management doctrine and crew rest/work cycles, provision of pharmacological aids, or as a selection tool for identifying the best performers. A recent study (Ref (5)) directed at exploring the feasibility of neuroelectric monitoring of sonar operators used highly trained sonar operators and investigated signal detection and signal recognition in a simulated sonar task. During presentation of sonar targets event-related potentials (ERPs) were recorded from a number of electrode sites over a 1750 msec recording period (Fig 4). Results revealed that several ERP components were significantly related to some aspect of detection and/or recognition. Figure (5) demonstrates results for targets correctly recognized. A positive response is demonstrated by a

downward deflection of the large P300 wave forms. These data identified that ERP components may be useful in evaluating detection and recognition performance. Utilization of a neuroelectric monitoring system aboard ship as a means of identifying deviation of attention/recognition (that is decrement of performance) in sonar operators has been contemplated. To date, no such system has been implemented. The following issues, similar to those expressed about physiological monitoring in the diving community, would have to be addressed before implementing such a monitoring system: (1) compliance, (2) means of instant data analysis and display of results, (3) durability and upkeep of equipment in an at-sea environment and (4) supervisory monitoring.

IN-FLIGHT MONITORING

Attempts at in-flight monitoring of physiological responses are not known. In the 1960s NASA supported an effort in which aircrew physiological response was recorded during flight operations over Vietnam. Although the number of subjects and physiological variables was limited, it was surprising to discover that carrier launch and recovery operations were more stressful (physiologically) than combat (Refs 6, 7). With aircraft design progression that has resulted in development of higher thrust-to-weight rates, reduced wing loads, and maneuverability that expose aircrew to greater than 10 Gs for sustained periods of time, an extensive need for better understanding of physiological response has been created. Proper assessment of the magnitude of response (physiologically) to aviation task loading is by in-flight monitoring of selected physiological responses.

AIRCREW FATIGUE

Based on a Chief of Naval Operation's guidance, an effort to investigate fatigue in the Navy's Anti-Submarine (ASW) patrol community was initiated. The directions were to assess whether fatigue exists, and if found, determine the effect on flight and mission performance.

Of the many definitions of fatigue, "task-induced" fatigue appears to best fit the Navy's operational environment. It is a fatigue produced by long hours of work in a taxing environment where loss of efficiency is attributed to both physiological and psychological factors. The concern about fatigue during sustained flight operations is one of both safety of flight and mission completeness.

The literature reveals an extensive amount of work in the area of fatigue and the varied methods of monitoring fatigue in aviation environments, dating back as early as the 1930s. Emphasis has most often been directed at cargo and transport aircraft conducting trans-oceanic, multihour, and multicrew

flights (Refs 8, 9, 10) with a few studies addressing tactical jet flights during carrier operations (Refs 11, 12) and even fewer in the ASW community (Refs 13, 14). It is quite clear that the level of fatigue can vary by job task. In fact, with dependency on operational tempo and lack of in-flight relief, fatigue may at times be more prevalent in the non-flight deck crew.

Physiological parameters frequently identified as indices of fatigue are: (a) varied endocrine responses such as blood catecholamines and urine levels of cortisol, 17-hydroxycorticosteroids, sodium/potassium concentration, urea, and creatine levels, (b) heart rate and electrocardiographic (ECG) response, (c) electromyogram (EMG) for assessment of muscle tension, (d) body temperature, and (e) muscular strength.

Routine collection of blood during in-flight periods (even in a multicrew sized aircraft) for blood levels of fatigue indices is (1) not easily accepted by the crew and (2) is not feasible because of a need to centrifuge blood samples and freeze them immediately. Therefore, urine samples collected during or at pre-post flight times and stored for later analysis have been a reasonable approach. Monitoring of variables such as heart rate, EKG, and EMG have been assessed in previous studies using varied gear driven tape recorders (Ref 15), telemetry systems (Ref 16), and limited solid state recording devices (Ref 17). In large multicrew aircraft such monitoring by medical personnel can be accomplished using more laboratory type monitors such as magnetic tape recorders, strip charts, etc.

A recent series of studies addressing in-flight fatigue in Navy ASW P-3 aircraft during overseas deployment have been conducted. Each aircrew member of a selected P-3 crew (usually 9 crewmen) was assessed physiologically (blood chemistries, muscular strength, aerobic fitness, etc.) prior to a 6 month deployment. While on deployment selected physiological parameters, as described above, were monitored/collected during actual multiple ASW flights (Fig 6). Following return from deployment, performance assessment data as conducted during pre-deployment were again collected. As expected, analysis of the data revealed significant changes in fatigue indices during flight, as well as, over a 6 month deployment period (Ref 14).

The process of physiologically monitoring ASW aircrewmembers during operational flights proved to be very difficult with the loss or non-acceptance of much of the data. Timing of data collection could not be controlled (mission operation interference), equipment idiosyncratic responses could not be easily corrected during flight, and efficient processing of blood and urine samples in field conditions versus sophisticated laboratory environments stimulated considerable concern about the size of the "standard deviation" in the data.

IN-FLIGHT CARDIAC STRESS

Naval/Marine Corps aviators flying high performance aircraft are exposed to frequent and repeated environmental and operational tasks, e.g., excessive \pm G loading, high oxygen demands, high temperatures, barometric pressure changes, disorientation, extreme visual tracking requirements, etc. These tasks pose physiological stresses/demands that can degrade performance. Studies are beginning to show that subjects whose energy requirements, metabolic activity, thermal, and cardiopulmonary states are least disturbed by the stress of high performance flight will perform best and become least fatigued during repeated aerial task loading (Refs 18, 19). During aerial combat, aviators use a spectrum of G levels varying in a continuous manner called the Aerial Combat Maneuver (ACM). The G envelope in which they fly may range from -3 to $+10 G_z$. Although ACM is a common flight environment, there is limited knowledge of the human tolerances to this environment.

Concerns about the effect of physical fitness on cardiac stress during high performance flight initiated a study in which G-load and heart rate response were collected during air combat maneuver (ACM) training flights. Several naval fighter pilots flying ACM training flights on a Tactical Air Combat Training System (TACTS) range were used as subjects. Heart rate response was collected every 2.5 seconds during flight by an eight channel solid state recording device (Fig 7). The monitor was attached by 3 ECG chest leads and was carried in the aviator's flight suit pocket. Aircraft flight responses were collected by a telemetry device attached to the aircraft wing which transmitted real-time data to a ground based computer system. Results demonstrated significant changes in heart rate during all phases of the flight profile (Fig 8) with inverse relationship between heart rate response and level of fitness.

The significant difficulty encountered with physiologic monitoring in this operational setting was the necessity to collect continuous heart rate response due to an inability to start/stop the monitor during flight. This necessitated extensive postflight data analysis. Additionally, a difficulty of extreme interest was the lack of accurate time-phasing of heart rate response with specific aircraft maneuvers because of the noncommunication between the two monitoring systems. For the most accurate human response data collection in an operational setting, there must be provisions for sequencing of a given response to the operational task in order to best determine "cause and effect".

IN-FLIGHT MONITORING DEVICES

In the latter part of the 1960's, the U.S. Navy developed an in-flight monitor called the Bio-Pack (Ref 15). The Bio-Pack consisted of a small gear driven 8 channel reel to reel recorder with a recording time of 40 minutes. Physiological variables monitored were ECG, body temperature, voice, cockpit acceleration, and temperature. The Bio-Pack was carried by the aviator on his knee board or map case with minimal interference. In 1975 the U. S. Air Force expanded the Bio-Pack by increasing its recording time and making it a gear driven cassette tape recorder. By the late 70's the Navy again expanded the recorder by developing a data analysis program and expanded the original 8 channel recorder to a 32 channel recorder and changed the name to In-flight Physiological Data Acquisition System (IFPDAS). When these gear driven data recorders were used in tactical jet aircraft, the prevalent difficulty was periodic tape speed fluctuations due to periods of excessive acceleration force on the tape recorder. Other operational constraints have been intermittent signals from the transducers, fixed data sampling rates, excessive maintenance efforts, and incompatibility between the microprocessor and other data processing units. The goal of in-flight physiological monitoring has been to accurately monitor and collect as many physiological responses and environmental data points during flight as possible with minimal interference to the pilot. A monitoring device capable of doing this must be small in size and self contained with multiple channels and expanded memory capability. Using today's state of the art in microprocessing and memory technology, the Navy has recently designed a Solid State Physiological Inflight Data Recorder (SSPIDR) for use in aeromedical flight test operations (Fig 9). "The SSPIDR incorporates analog to digital physiological signal conversion, a Motorola 68000/6/32 bit microprocessor, 512K x 16 bit memory, and battery power supply in a 13 x 15 x 5 cm package which fits in an aircrewman's survival vest. Available data channels include three electrocardiogram, one electroencephalogram, one respiratory rate, two electrooculogram, three linear acceleration, eight temperature, one pressure, and a digital event marker. On-board software permits variable sampling rates and gain. The sampling rate and amplification may be changed according to predefined flight or physiological conditions" (Ref 20). The Navy has also recently initiated a contract with a bioengineering company to design and fabricate a miniature O₂/CO₂ transducer for use in the SSPIDR.

Outyear plans for the SSPIDR include monitoring of physiological responses during wearing of chemical defense ensemble, sustained operations, use of varied pharmacological agents, parachuting, impact/acceleration, and multiple cognitive task regimes. The device will also be made available for other Navy community uses as applicable. The SSPIDR, however, is not yet designed for water immersion.

CONCLUSIONS

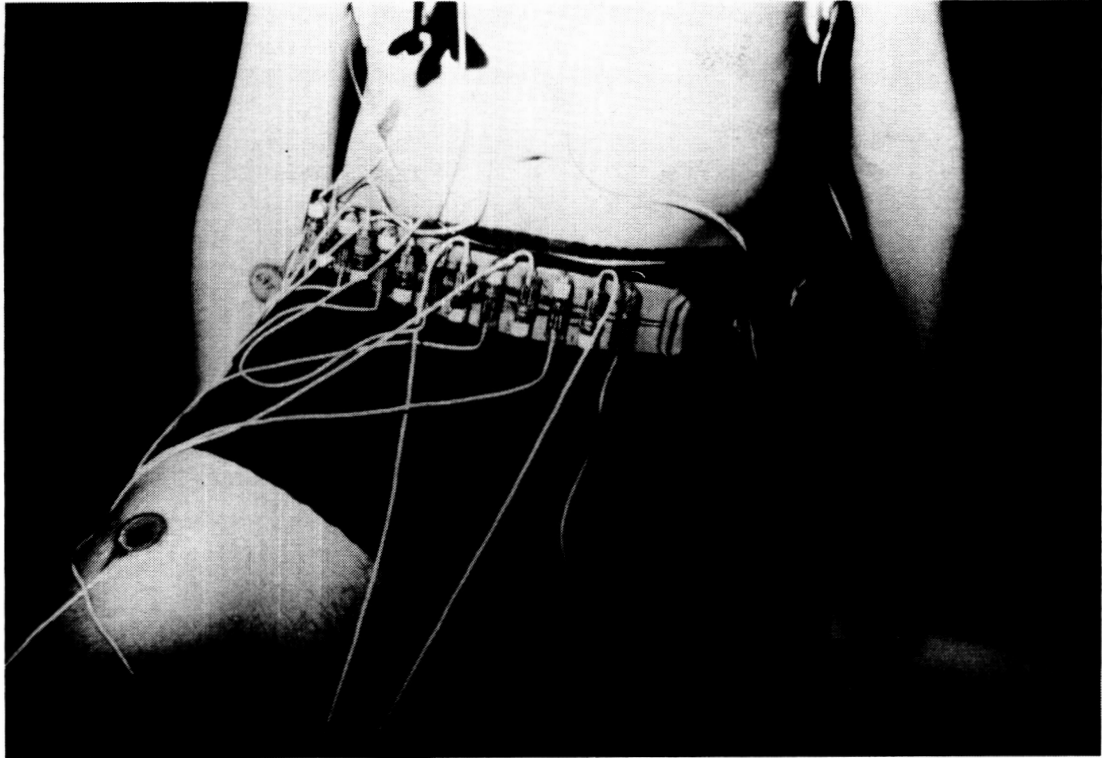
Physiological monitoring is necessary to identify the physiological requirements of operational tasks, how well the individual performs within those tasks, and the success or failure of the man-machine interface. In the Navy, operational settings are numerous and unique. The challenges of physiological monitoring in the varied operational settings are also extremely numerous. The general difficulties of monitoring are, however, most likely commonplace among the settings and among the services. These challenges include, but are not limited to, environmental extremes, acceptance of use by test subjects, data transfer, data interpretation, and capability of relating collected data to valid operational relevant criterion measures.

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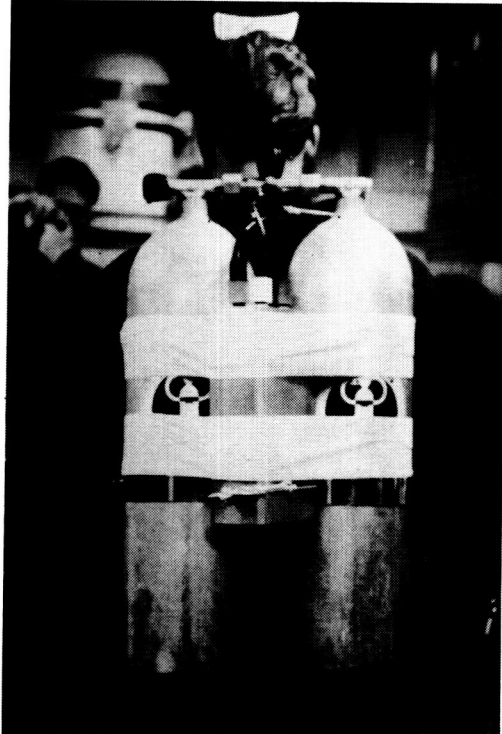
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1. Diver Heat Flux and Thermal Monitoring System



2. Attachment of underwater physiological equipment

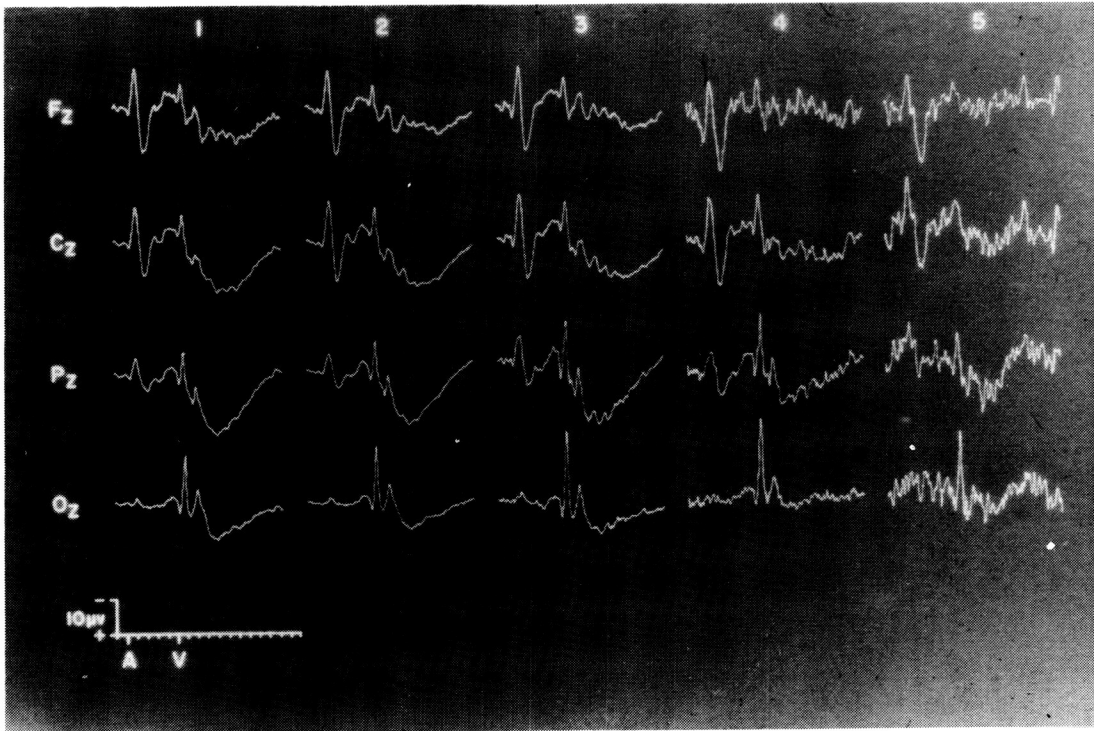


3. Navy Diver with a physiological data acquisition system taped to air tanks

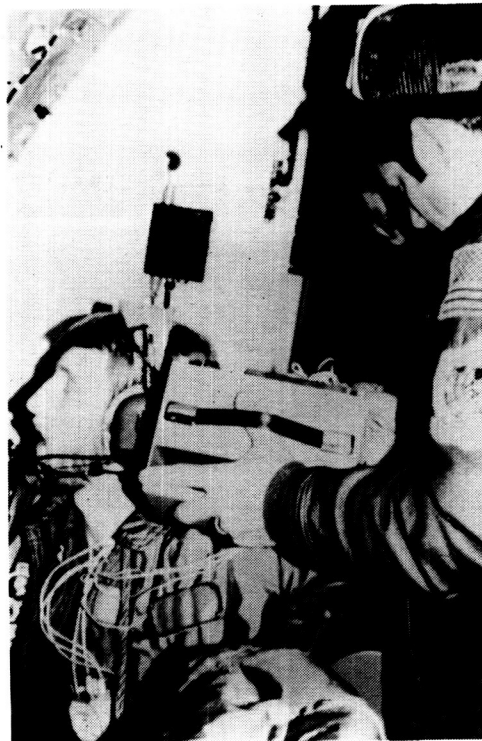


4. Attachment of event related potential (ERP) recording electrodes on a U. S. Navy sonarman

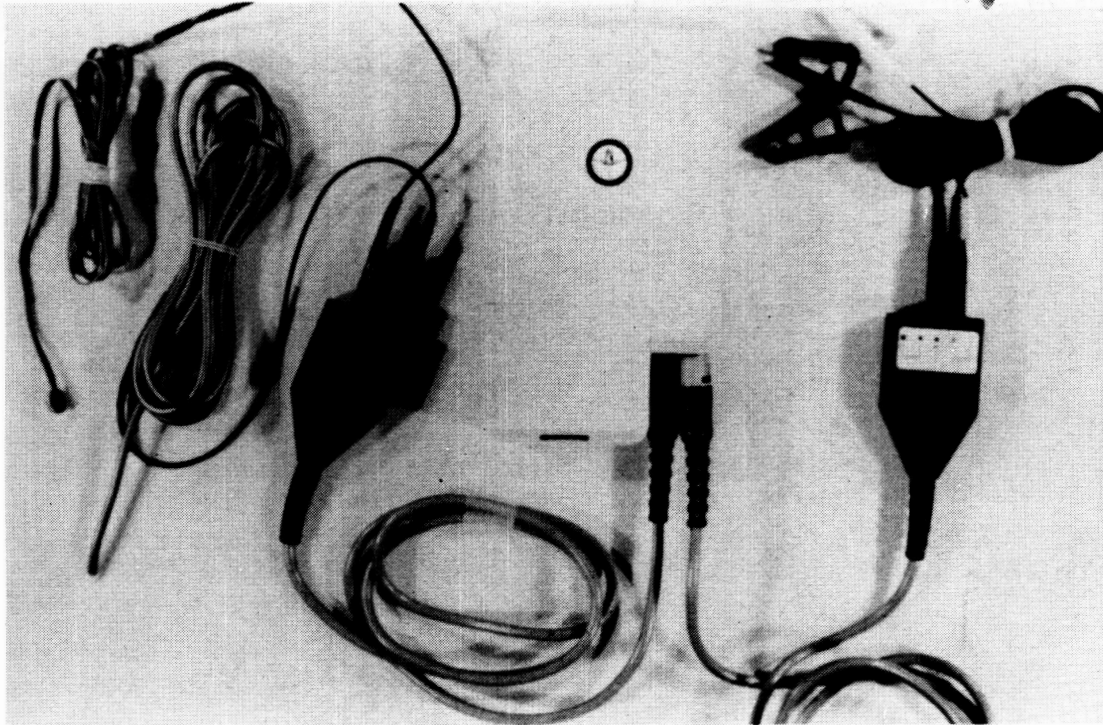
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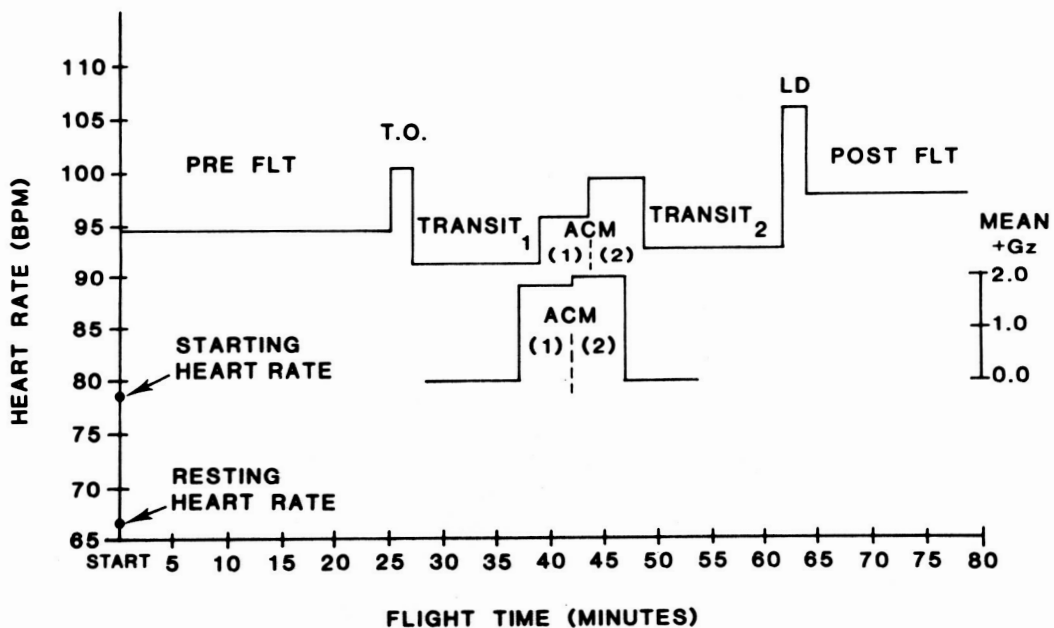
5. Event related potential (ERP) recordings from four skull sites: F₂, C₂, P₂, O₂. Positive response to target recognition is demonstrated by downward deflection of the large P300 wave forms



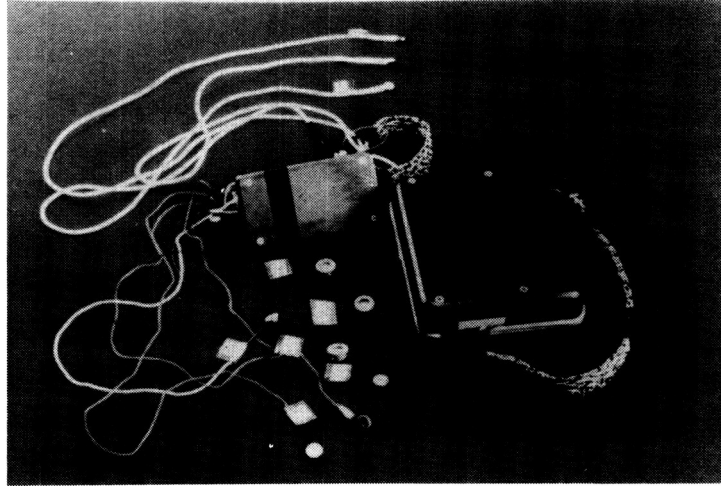
6. In-flight physiological monitoring of an antisubmarine warfare patrol aircraft aircrewman



7. Eight-channel solid-state recording device (Trade name: Vitalog (Vitalog Corp))



8. Mean heart rate and $+G_z$ response during Tactical Air Combat Training System (TACTS) Range ACM flights for 11 aviators during 23 flights. PRE flt = preflight; T.O. = takeoff; transit = flight to TACTS range. ACM 1 and 2 = individual ACM events (flights); transits = return flight to base; LD = landing, Post Flt = postflight (Banta et. al., Naval Aerospace Medical Research Laboratory, TR # 1329, January 1987)



9. Solid-State Physiological Inflight Data Recorder (SSPIDR)
used for aeromedical flight test operations