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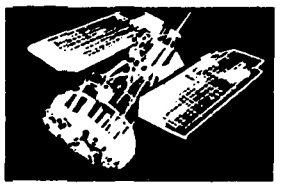
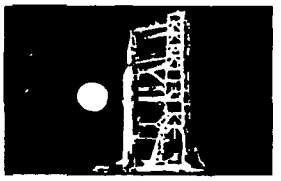
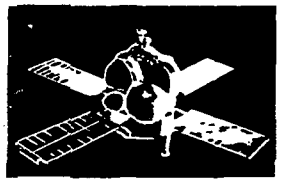


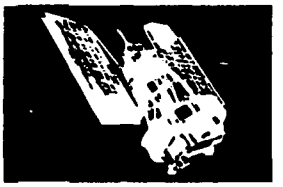
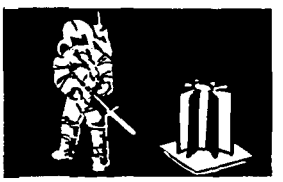
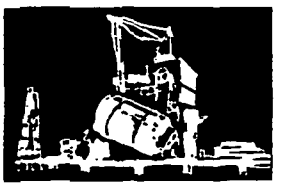

GE NO. 70SD5414

IMBLMS
PHASE B4

ADDITIONAL TASKS
TASK 4.0

General Purpose Bioamplifier Study
FINAL REPORT

IMBLMS

Contract NAS 9-10741
Phase B4

GENERAL ELECTRIC

GE No. 70SD5414

FINAL REPORT

IMBLMS PHASE B 4

ADDITIONAL TASKS

TASK 4.0: GENERAL

PURPOSE BIOAMPLIFIER STUDY

CONTRACT NAS9-10741

GENERAL ELECTRIC CO.
SPACE DIVISION

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GENERAL PURPOSE BIOAMPLIFIER STUDY

I. INTRODUCTION

During the course of the definition and preliminary design phases of IMBLMS (Integrated Medical, Behaviorial and Laboratory Measurement System) it became obvious that a large number of physiological signal conditioners would be required to implement the measurements desired for optimum system usefulness in extended space flight. Many of these signal conditioners had similar attributes in that they received small physiological potentials as an input from some form of electrode connected to the subject and amplified this input to several volts for display and/or subsequent analysis and storage by a data handling system. The signal conditioners defined above are termed biopotential amplifiers. The measurements concerned are EEG (electroencephalography), EMG (electromyography), EOG/ENG (electrooculography/electronystagmography), ECG (electrocardiography), and VCG, (Vectorcardiography). The question arises as to whether or not a single signal conditioner design could not be used for all of the above measurements and if so, would it be desirable to use such a signal conditioner in IMBLMS. While the measurements described above require signal conditioners which are similar, there are still significant differences in the manner in which the measurements are actually implemented. For example, in the case of ECG, not only must the signal conditioner accept the input from a pair of electrodes, it must also provide for switching from one set of electrodes to another (i.e., various lead configurations). The VCG signal conditioner must provide three outputs properly weighted and phased for a correct representation of the three components of the vector potential of the heart. Other dissimilarities which must be considered are: different electrodes for different measurements (hence different input requirements on the signal conditioner), wide ranges of input signals (10 uv to 10 mv)

and differing bandwidths (DC to 1 KHz).

In order to properly assess whether a general purpose amplifier (GPA) is more desirable than a series of dedicated amplifiers for use in IMBLMS, it is first necessary to define such a general purpose amplifier and ascertain whether its design would be within the present state-of-the-art. The technique chosen to define the GPA is to determine its requirements based on known inputs and outputs and to create a set of specifications for its major characteristics. These specifications can then be used to perform a trade-off study of the GPA versus dedicated amplifiers in the IMBLMS. Figure I-1 represents the above study organization in block diagram form.

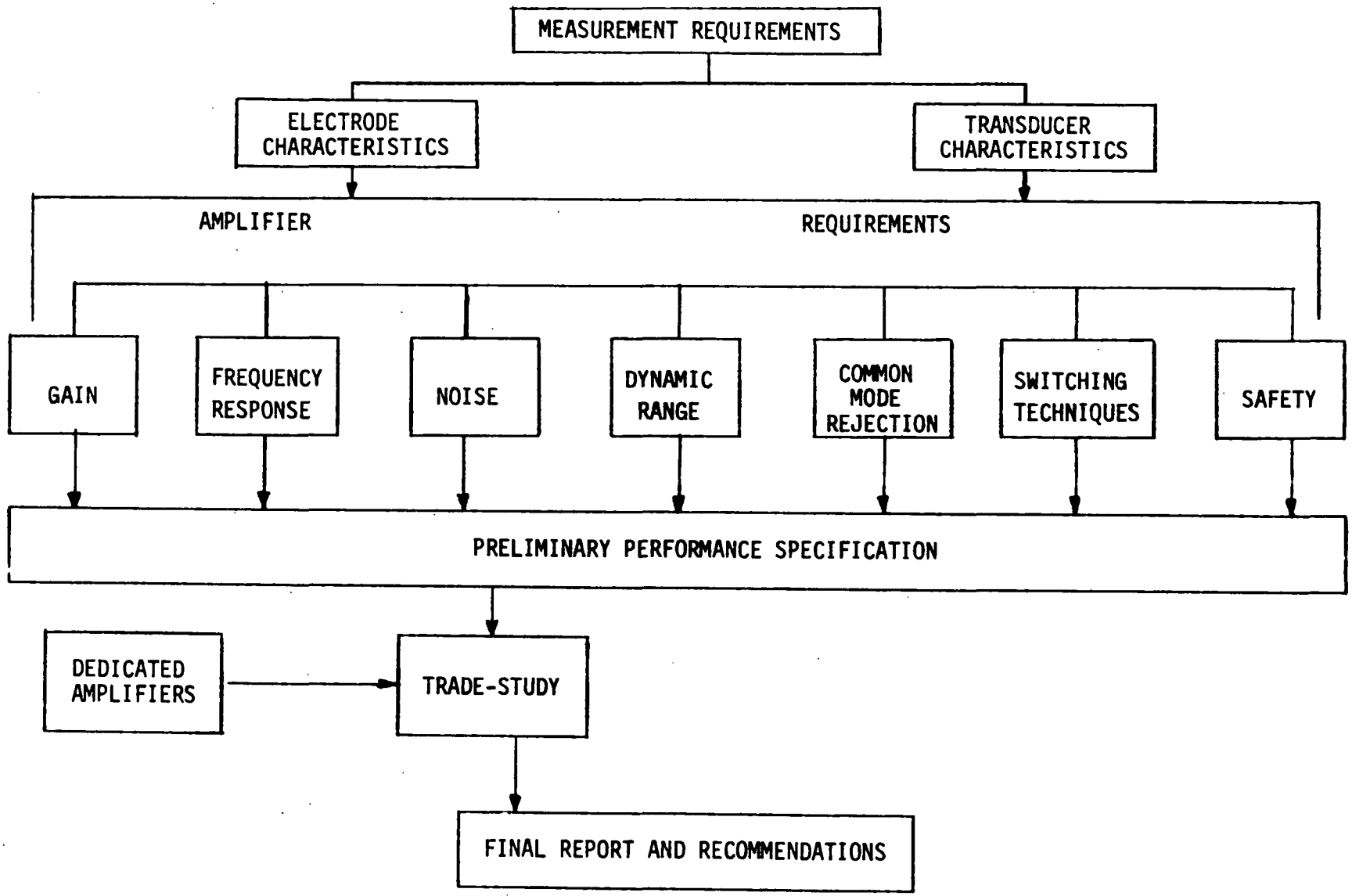


FIGURE I-1 - TASK IV - STUDY ORGANIZATION

II. MEASUREMENT REQUIREMENTS

In order to determine for what measurements a GPA could potentially be used in the IMBLMS, the Phase B-4 Measurement Requirement Sheets (MRS) were analyzed and the pertinent electrical characteristics were extracted to serve as a basis for defining some of the electrical characteristics of the GPA. A list of the selected measurements appears as Figure II-1 and a table of the pertinent electrical characteristics appears as Table II-1.

It is clear from the list of electrical characteristics that the GPA must be capable of operating as a differential amplifier having a common mode rejection (CMR) of better than 100 dB and an input impedance of greater than 40 megohms. It must be capable of resolving signals as small as 10 uvolts and must have an input noise no greater than 5 uvolts peak to peak from .2 to 1000 Hz. DC response is required for temperature, GSR/BSR and blood pressure.

Although output requirements are not given as part of the measurement requirements, it will be assumed that a full scale output of $\pm$10 volts is desired and the gains required of the GPA can thus be determined.

MEASUREMENTS	SENSOR
• ELECTROCARDIOGRAM (ECG)	ELECTRODES
• VECTORCARDIOGRAM (VCG)	ELECTRODES
• PHONOCARDIOGRAM/VIBROCARDIOGRAM (PCG/VbCG)	MICROPHONE
• ARTERIAL BLOOD PRESSURE	PRESSURE TRANSDUCER
• VENOUS BLOOD PRESSURE	PRESSURE TRANSDUCER
• BALLISTOCARDIOGRAM (BCG)	ACCELEROMETER
• ELECTROENCEPHALOGRAM (EEG)	ELECTRODES
• ELECTROMYOGRAM (EMG)	ELECTRODES
• ELECTRO-OCULOGRAM (EOG)	ELECTRODES
• GALVANIC SKIN RESISTANCE (GSR)	ELECTRODES
• SKIN TEMPERATURE	THERMISTOR/THERMOCOUPLE
• EAR CANAL TEMPERATURE	THERMISTOR/THERMOCOUPLE

Figure II-1—MEASUREMENT REQUIREMENTS

MEASUREMENT	MEASUREMENT CHARACTERISTICS	SIGNAL SIZE	FREQUENCY
ECG	Biphasic, repetitive wave form	0-3 millivolts	.05-100 Hz
VCG	Biphasic, repetitive wave form	0-3 millivolts	.05-100 Hz
PCG/VbCG	Vibrations through the thoracic cavity caused by cardio-vascular action	- - -	Selectable .1-20 Hz, 10-30 Hz, 30-500 Hz, .1-1,000 Hz
Blood Pressure Arterial Blood Pressure Venous	Pressure (cyclic 0-250 mm Hg) Pressure (steady 0-15 cm H_2O)	0-250 mm Hg 0-15 cm H_2O	- - - - - -
Ballistocardiogram	Resultant accelerations on the body mass produced by ventricular ejection	0.0 $\pm$ 3.0 cm/sec.^{2} Major Axis .3 to .03 rad/sec. Angular 0- $\pm$ .3 cm/sec. Minor Axis	.05-500 Hz - - -
EEG	Biphasic, repetitive waveform	10-200 μV	.2 to 100 Hz
EMG	Biphasic, random waveform	0-5 mV	.5-1,000 Hz
EOG	Biphasic, repetitive waveform	10 μV-1 mV p-p	.14-100 Hz
*GSR (BSR)	Change in skin resistance (random wave)	R 0-100 K	0-1 Hz
Temperature	Dependent on transducers	- - -	- - -

*GSR vs. BSR Galvanic Skin Response is a change in the resistance of the skin between two selected points it varies from 0-4 K Ω. Basal Skin Resistance (BSR) is the Basal Resistance of the skin on top of which occurs the GRS. BSR varies from 10^3 to 10^6 ohms.

TABLE II-1-- PERTINENT ELECTRICAL CHARACTERISTICS

MEASUREMENT	INPUT IMPEDANCE	SIGNAL SOURCE IMPEDANCE	ELECTRODE CURRENT
ECG	> 40 meg.	1-40 K Ω	< .5μ A Normal < 10 μ A Abnormal
VCG	> 40 meg.	1-40 K Ω	< .5μ A Normal < 10 μ A Abnormal
PCG/VbCG	Dependent on transducer	Dependent on transducer	N/A
Blood Pressure Arterial Blood Pressure Venous	- - - - - -	- - - - - -	- - - - - -
Ballistocardiogram	- - -	- - -	- - -
EEG	10 meg. diff.	1-40 K Ω	.5 μ A
EMG	40 meg. diff.	1-40 K Ω	.5 μ A
EOG	10 meg. diff.	1-40 K Ω	.5 μ A
*GSR (BSR)	- - -	- - -	- - -
Temperature	Dependent on transducers	- - -	- - -

MEASUREMENT	FREQUENCY RESPONSE	ROLL-OFF	HARMONIC DISTORTION	COMMON MODEL REJECTION
ECG	±.5 db .14-90 Hz	10 db/octave @ 100 Hz @ .05 Hz no more than 3 db from that at .14 Hz	1%	100 db
VCG	±.5 db .14-90 Hz	10 db/octave @ 100 Hz @ .05 Hz no more than 3 db from that at .14 Hz	1%	100 db
PCG/VbCG	±.5db 20-900 Hz upper 3 db 1000 Hz lower 3 db 10 Hz	6 db/octave	2%	---
Blood Pressure Arterial Blood Pressure Venous	--- ---	--- ---	--- ---	--- ---
Ballistocardiogram	±.5 db 1-100 Hz	10 db/octave @ 100 Hz	---	---
EEG	±.5 db .2-90 Hz	10 db/octave @ 90 Hz	2%	100 db
EMG	±.5 db .5-900 Hz	10 db/octave @ 100 Hz	2%	100 db
EOG	±.5 db .1-90 Hz	10 db/octave @ 100 Hz	2%	100 db
*GSR (BSR)	---	---	---	---
Temperature	---	---	---	---

MEASUREMENT	SENSITIVITY	NOISE	AMPLIFIER INPUT CONFIGURATION
ECG	12.5 μ V	10 μ V p-p	Differential
VCG	12.5 μ V		Differential
PCG/VbCG	---	---	Single-ended
Blood Pressure Arterial Blood Pressure Venous	± .5 mm Hg ---	--- ---	Dependent on transducer
Ballistocardiogram	Major Axis = 1% Angular Axis = 1 mm/sec.^{2} Minor Axis = .003 rad/sec.	--- --- ---	Dependent on transducers
EEG	10 μ V	5 μ V p-p	Differential
EMG	10 μ V	5 μ V p-p	Differential
EOG	12.5 μ V	10 μ V p-p	Differential
*GSR (BSR)	1%	---	Differential
Temperature	---	---	Dependent on transducer

III. INPUT DEVICES

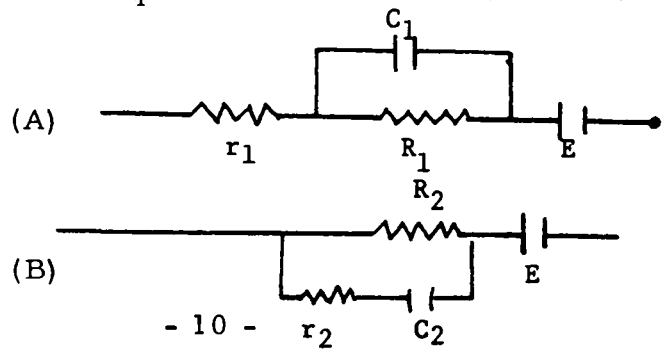
In order to provide a more intensive study of the input requirements of the GPA various types of transducers and electrodes were evaluated to determine their output characteristics.

1. ELECTRODES

The input impedances recommended in the MRSs is based on the use of a floating type wet electrode. The impedance of this electrode is typically less than 10,000 ohms but may vary from 1 to 40,000 ohms over reasonable measurement periods (less than 8 hours). In an attempt to define the input characteristics which might be encountered by multi-parameter bio-potential amplifier, the characteristics of several other types of electrodes are presented. However, after only a superficial look into the literature, the task becomes much more involved than originally anticipated. In an attempt to simplify this involved task, electrodes will be classed in three broad types. The specification typical for each type will be presented as well as the usual use of each type, i.e., which type of electrode is used for each bio-potential measurement.

Some electrodes will not specifically be suited for manned space application, but in the interest of completeness, they too are mentioned.

To begin the classification of electrodes, the first step would be to try to define what the electrode looks like from the amplifier. Two popular and generalized versions of equivalent circuits for electrode skin interfaces are shown below:



The voltage E is the half cell potential generated by the electrode. The half cell potential is generated by the metals in the electrode and the electrolysis of the skin or the electrode paste.

The classification of electrodes chosen for our purposes has three general categories:

- Wet
- Dry
- Insulated

Wet electrodes are considered to be any electrode which uses conductive material to reduce the surface resistance. This material may be artificial i.e., jelly, paste, etc. or natural, i.e., tissue fluids made by injury.

Dry electrodes are those types of electrodes which do not purposely try to reduce the surface resistance by the addition of some conducting medium.

Insulated electrodes are those which place an insulating material between the conducting surface and the electrode. Each of these large divisions can be further broken down into different application methods within each division. The largest division is the wet which traces its origin back to the 1800's when the ECG's were recorded from subjects who had their bare feet and hands immersed in buckets of saline. This type of electrode has progressed to the type NASA calls semi-wet which is a very thin layer of electrolyte (approximately 10M Ringers Solution), over the electrode surface. Of the wet electrodes, there are three basic types: non-floating, floating, and invasive. Non-floating electrodes are those which have direct contact with the skin surface. These electrodes sit over a skin site which has been prepared by removal of the cornified skin layer or saturation with an electrolyte. Another approach to this type of electrode is to spray the skin with silver or some other metallic conductor and then attach the lead wire by some gluing mechanism to this metallic surface,making these silver spot terminals on the subject.

Floating electrodes are by far the most widely used. With this type of electrode, the electrode surface rides on a layer of electrolyte which has contact with skin surface. The electrode is then held in place by masking the surface. The present NASA electrode is of this type. A variation of this method is the use of an electrolyte which will also serve as the mastic for electrode attachment. This was the type of electrode used in B-3 for the EEG. The Adey cap also uses a modified floating electrode. In this case, the electrode surface interfaces with a sponge impregnated with electrolyte and the sponge touches the skin surface. This technique has been found very effective for EEG recording.

Invasive electrodes are those which overcome the high cornified epithelial resistance by penetrating it. These electrodes are usually called pin and needle electrodes and pierce the skin from .1 mm to 4 cm. A rather good invasive electrode was one designed from a common Nut Meg grader. The sharp grating surface was placed against the skin and pressed. The small projection penetrated the cornified layer and made a good low resistance electrode.

Figures III-1-1 and III-1-2 and Table III-1-1 are given in an attempt to define some characteristics of wet electrodes which an all purpose amplifier might encounter.

Dry electrode information is somewhat more limited than the information on wet electrodes, since they are not in general use and the characteristics listed are from only one source.

ELECTRODE	USE	IMPEDANCE
SILVER SCREEN	ECG	20K - 10 M Ω

As with the dry electrodes, the information below is from one source:

ELECTRODE	USE	d.c.	CAPACITANCE
ALUMINUM/ALUMINUM OXIDE	ECG	400 M Ω	5000 pF @ 50 Hz

Both the dry and capacitive electrodes use buffers. A circuit diagram of a typical circuit is included as Figure III-1-3.

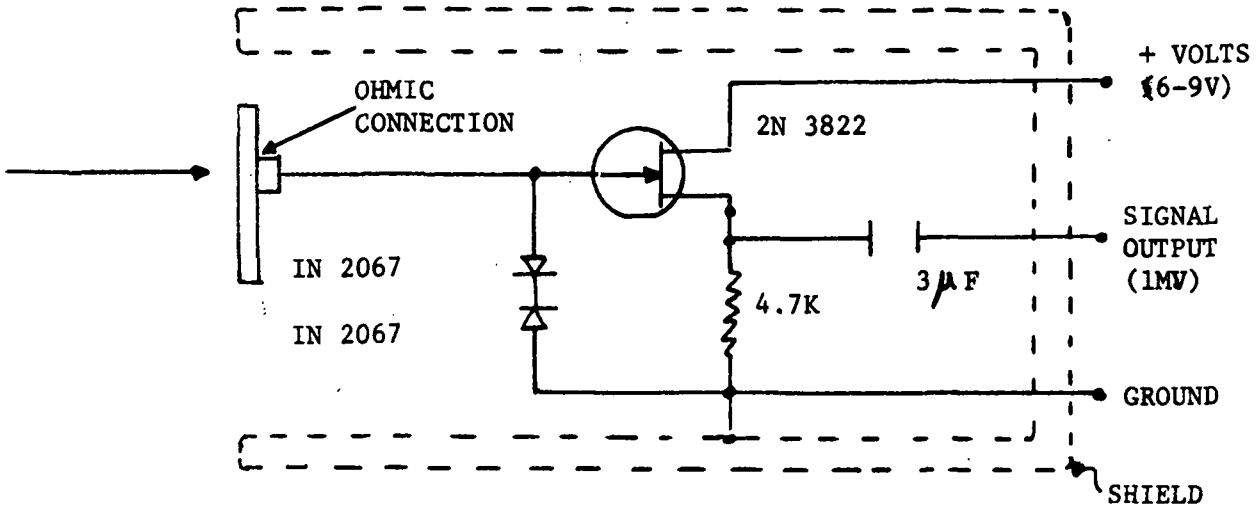


FIGURE III-1-3. TYPICAL BUFFERED ELECTRODE

These buffers can also be used with wet electrodes with the advantage that they provide a constant low impedance source to the signal conditioner. Also the input current of the signal conditioner is no longer of importance, since the current drawn from the electrode is determined by the buffer.

2. TRANSDUCERS

For the sake of completeness, the transducers required for temperature, blood pressure, GSR/BSR and ballistocardiogram were examined and some typical outputs determined.

Typical transducer output characteristics are given below for the type of measurement specified in the paragraph heading. These characteristics are to be considered typical as well as the transducer type given as an example. In some cases more sensitive transducers are required, but these parameters should be near those chosen as an example.

FIGURE III-1-1

IMPEDANCE-FREQUENCY CHARACTERISTICS OF ELECTRODES APPLIED TO HUMAN SUBJECTS

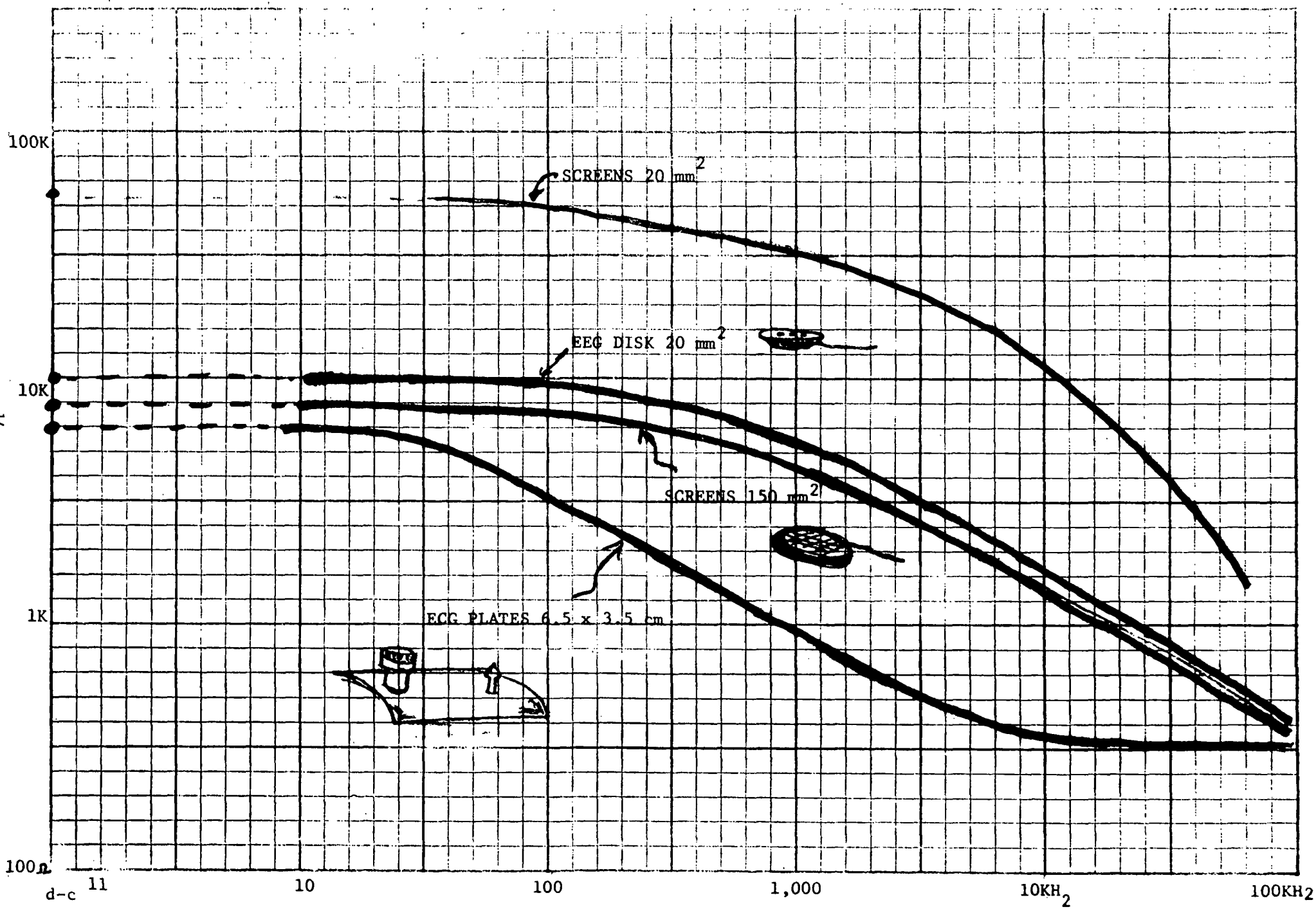


FIGURE III-1-2. ELECTRODE IMPEDANCE VS. FREQUENCY

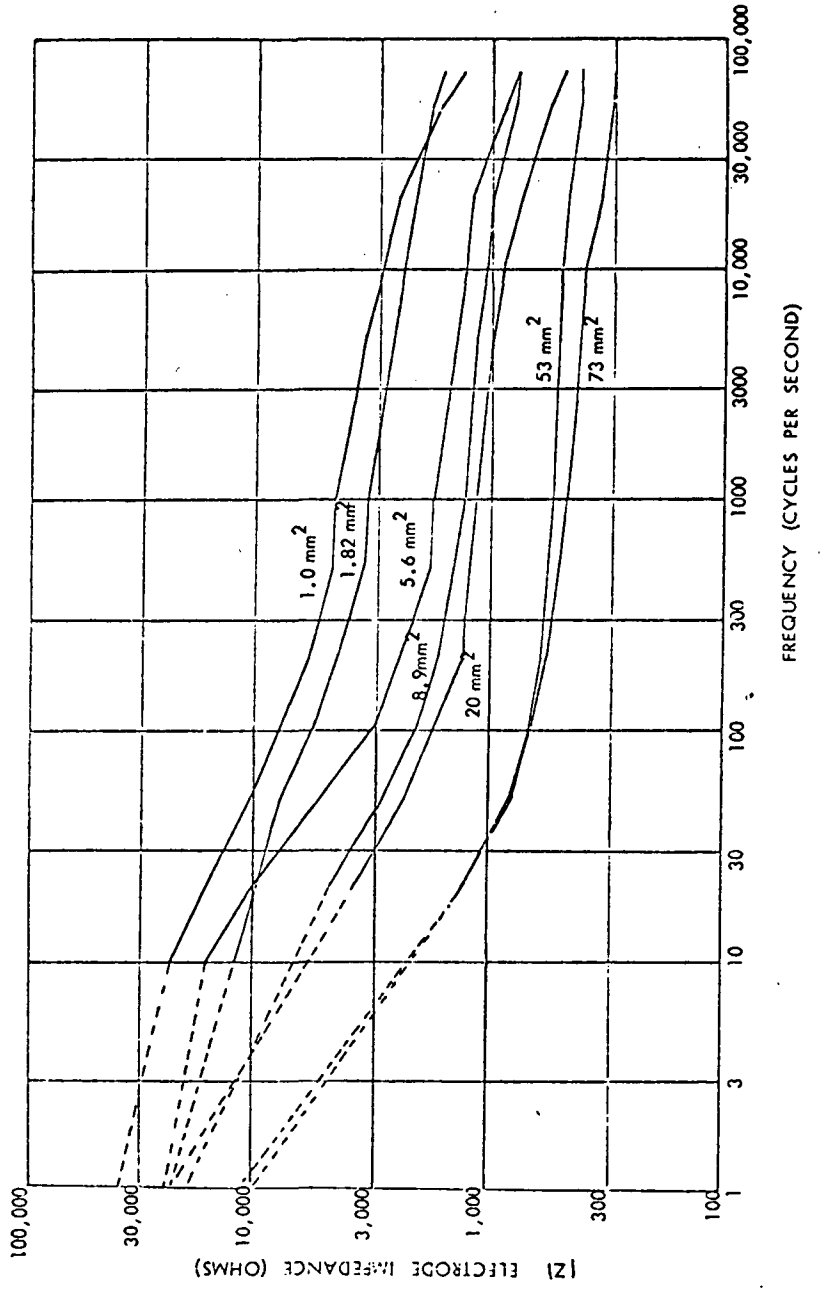


TABLE III-1-1

ELECTRODE TYPE	USE	RESISTANCE	
		D.C.	A.C.
NON-FLOATING			
Grater (Large)	ECG	2-10K Ω	≈300Ω
Grater (Small)	ECG (Chest)	6K Ω	
Metalized Skin	ECG		50K
FLOATING			
Plate	ECG (Leg)	2-10K Ω	≈300 Ω
Cup	ECG, EMG	2-7K Ω	
Beckman	ECG, EMG	.5-2K Ω	
Silvered Nylon	EMG	100K Ω	
Silver Spheres	EEG (Exposed Cortex)	≈10K Ω	
INVASIVE			
Needle	EEG, EMG	See Figure 2	
Micro-Needle	Single Cell		
Cutting	Subcutaneous EMG, ECG		

a. Skin Temperature Measurement

To measure skin temperature two types of transducers were selected: thermistor and thermocouples.

Thermistor Characteristics:

Output Resistance - Low (10K to 50K)

Signal Level - High

Accuracy - High

Noise Level - Low

The impedance (resistance) of the thermistor varies with temperature in a non linear manner but can be linearized and accurately calibrated over the temperature range of concern. A bridge arrangement is recommended. External excitation is required (+5 volts). The bridge output can best be measured differentially. Output impedance can be in the 10 to 50K ohm range with output voltage signals of 0.5 to 1.0 volts. Self heating effects of the thermistor must be minimized. The sensor package is light, small in size, rugged in construction. Typical Vendors - YSI, VECO, FENWAL.

Thermocouples

Output Resistance - Very low

Signal Level - Low

Accuracy - High

Noise Level - Low

The output voltage of the thermocouple varies with temperature. Using a chromel-constantan junction and a cold junction ($0^{o}C$) an output of 1.26 mv can be obtained at $70^{o}F$ and 2.27 mv at $110^{o}F$. The output is accurate, repeatable and linear. Care must be taken that additional junctions are not built into the sensing loop or if a reference is not used, that ambient changes be compensated. Use of a differential amplifier is recommended.

The sensor package is small in size, rather fragile and very light.

Typical Vendors: OMEGA

b. Ear Canal Temperature Measurement

The ear canal temperature measurements will use a transducer similar to skin measurement task except for the form factor of the sensor.

c. Galvanic Skin Response (G.S.R.)

To measure the resistance or change in resistance of the subject's surface resistance, a transducer, as such, is not required. A bridge type arrangement will be used using three known resistance values with the fourth leg the subject's skin.

Transducer - None

Bridge Characteristics

Output Resistance	- Low (< 10K)
Signal Level	- High
Accuracy	- High
Noise Level	- Low

The G.S.R. measurement can be made through the use of a resistance bridge arrangement. Three legs will be accurate resistances while the fourth is the area under measurement. An accurate shunting resistance can be used in the fourth leg to set the differential output near null.

d. Ballistocardiogram

To measure low level body movements two types of transducers are required: angular and linear accelerometers.

Accelerometer Characteristics

Angular	Output Impedance	- 10K to 20K
	Signal Level	- 10V/Rad/Sec^2
	Noise	- Low -50 mv
Linear	Output Impedance	- Low (1 ohm)
	Signal Level	- High
	Noise	- Low < 5 mv

The selection of other proper accelerometers may be governed by size and sensitivity. However, in general, their outputs will be in the ranges specified. Examples are given below:

Linear Accelerometer - Gulton Ind. Series III

Excitation	-	15 volts, 400 Hz, 0.5 watt
Output	-	4 volts full scale into 4.3K ohms
Output Imp.	-	1600 ohms
Range	-	$\pm$0.1G to $\pm$100G

Angular Accelerometer - SystronDonner 4525

Excitation	-	$\pm$45 VDC
Output	-	$\pm$20 volts
Output Imp.	-	14K ohms
Noise	-	50 mv rms
Range	-	2 rad/sec^2 to 50 rad/Sec^2

e. Arterial Blood Pressure

To measure the arterial blood pressure a displacement transducer is typically used.

Measurement - Pressure (0 - 300 mm Hg)

Transducer - Volume Displacement

Characteristics

Output Resistance	200 ohms
Signal Level	50 mv/V_{in}/cm Hg

Accuracy	-	High
Noise	-	Low
Excitation	-	5-7 VDC
Vendor	-	Statham Mod. P23

The output of the pressure transducer varies as a function of the blood pressure and excitation voltage. A zero balance must be obtained at cabin or environmental pressure. The pressure range is from 0 to 300 mm Hg. with normal output of .0 to 11 millivolts.

The transducer is small and light weight.

e. Venous Blood Pressure

Venous blood pressure measurements will be similar to the arterial except for the use of a catheter in place of the cuff.

IV. AMPLIFIER REQUIREMENTS

1. Gain

The input dynamic range of the GPA must be capable of handling signals from 10 μv to 5 mv for biopotentials and 10 μv to 25 mv for transducer outputs. As shown in the summary of transducer characteristics there are some transducers which are capable of delivering volts of usable output and it is assumed the GPA would not be required if such transducers were chosen.

For the case of biopotential amplifiers, a signal somewhere in the spread of expected variations is chosen as a reference and this signal is then amplified to provide a nominal one volt output, e.g. for ECG 1 mv input equals 1 volt output for a gain of 1000. The signal chosen is typical of an expected "normal" signal. If we assume, therefore, that EEG represents a reasonable lower limit we can choose 50 μv input equals 1 volt output for a gain of 2×10^4. Since transducers are normally scaled to provide full scale output for full scale input to insure greatest accuracy and we have assumed $\pm$10 volts as an output signal spread, the upper limit of transducer inputs gives us the lowest gain required, e.g. $\frac{10}{25 \times 10^{-3}} = 400$.

Therefore the GPA must be capable of providing gains ranging from 400 to 20,000 and must provide this capability without exceeding the dynamic range of any of its stages of amplification.

2. Bandwidth

The bandwidth of the GPA must be capable of being switched depending on the measurement being performed (See Section IV-6). Overall bandwidth with no limitations will be DC to 1000 Hz (3 db). Switching of passive components will be used to limit this bandwidth in order to improve signal to noise without sacrificing an acceptable output. For example, a clinically acceptable

electrocardiogram can be achieved using a bandwidth from .14 Hz to 40 Hz; however, for accurate quantitative measurements an upper limit of 100 Hz is desired (some investigators insist on 500 Hz). The penalty paid for the increased bandwidth is increased high frequency noise content in the output signal.

3. Noise

The input noise requirement for the GPA is dictated by the measurement requiring the greatest sensitivity with the maximum bandwidth. Looking at Table II-1 we see that EMG will provide us with the requirement of 5 μv p-p noise over a bandwidth of .5 to 1000 Hz. Attaining this low a noise over such a broad bandwidth is a state-of-the-art requirement. By restricting the high frequency cut-off to 100 Hz, 5 μv p-p can be obtained consistently by using low noise junction FETS in the input stages.

For DC measurements utilizing transducers we are more interested in DC stablility versus time and temperature than we are in actual noise since the sensitivity and frequency requirements are reasonably moderate. Once again using matched junction FETS drifts of 10 μV/^{o}C and 100 μV/hr are attainable. These figures can be reduced by almost an order of magnitude using more sophisticated techniques for selecting and matching devices.

4. Dynamic Range

As discussed previously under Gain, the GPA must be capable of handling signals from 10 μv to 25 mv with a $\pm$10 volt output swing. This corresponds to an input dynamic range of approximately 70 db. In order to handle the gains required (400 to 20,000) a multi-stage design is required. The input stage must provide high input impedance, low noise, low voltage drift and excellent CMRR but should have no more gain than is required to assure that the second stage will not affect these input parameters. In addition to the

input differential pair, a second differential stage should be used in order to facilitate low frequency bandwidth limiting. Following a differential to single-ended conversion all succeeding stages will be single-ended and shall provide high frequency bandwidth limiting. The output dynamic range can be achieved by taking the output signal from different single-ended output amplifiers. See Figure IV-4-1. For a 25 mv signal the output would be taken from output #1, other signals would have their outputs taken from output #2.

5. Common Mode Rejection

In order to reduce the effects of electrical interference and hence keep overall output noise at a minimum, a differential amplifier configuration is used. The differential amplifier has the inherent characteristic that it amplifies the difference in the signals presented to its inputs and not the signals themselves (common mode signals); therefore, if noise or interference (60 Hz, etc.) appears at its inputs in phase, it will be rejected by the amplifier and will not appear at its output. The ability of an amplifier to perform in this fashion is determined by many factors, i.e., signal level, device non-linearity, device matching, input impedance, source impedance, etc.

Common Mode Rejection Ratios (CMRR) of 100 db are readily attainable with balanced sources and over a frequency range from DC to 100 Hz using matched junction FETS. With the source impedance required by the GPA, a degradation of approximately 20 db in CMRR can be expected with a source unbalance of as much as 100K. Since source unbalance will be determined primarily by the type of electrode used and its characteristics, a 100 db minimum CMRR is a reasonable specification, with a design goal specification of 120 db.

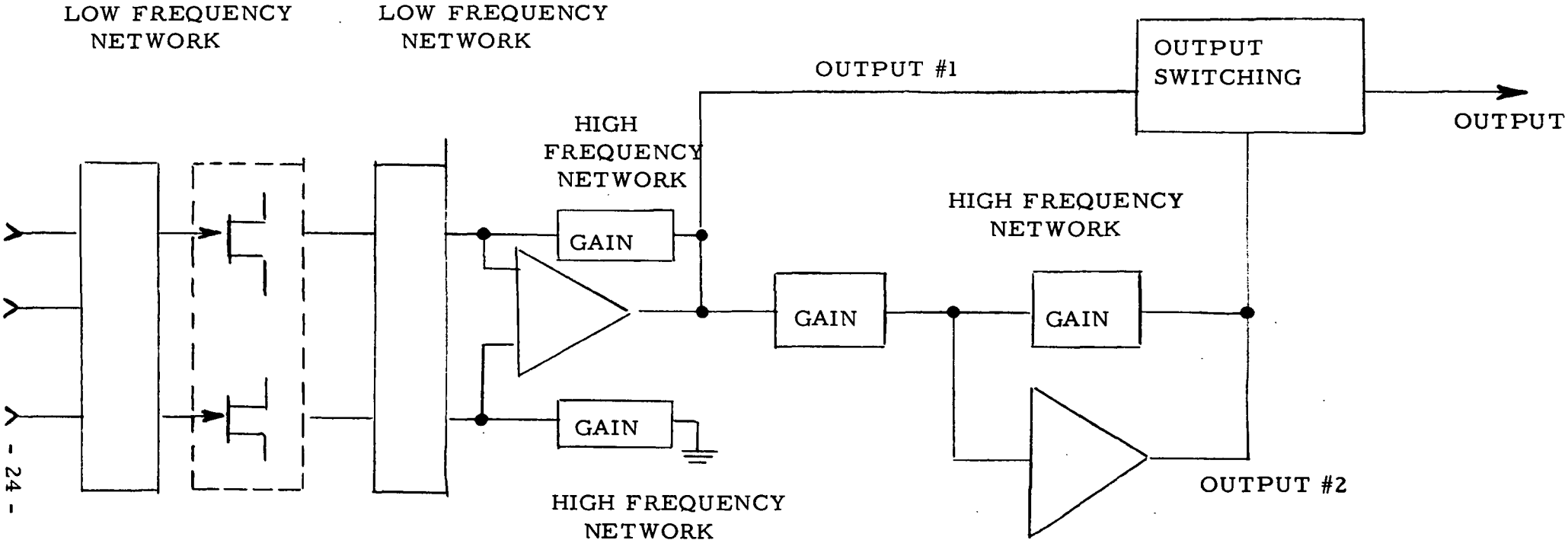


FIGURE IV-4-1 DIAGRAMMATIC GPA

Typically, the CMRR must fall somewhere between the limits.

6. Switching Techniques

In order to attain the flexibility required in order that the GPA be used to make a myriad of physiological measurements, it is necessary to use some sort of switching device or devices to implement gain and bandwidth variations and to provide for lead switching. From the system point of view, any switching device must be electrically operated so that completely automatic operation is possible. Either electro-mechanical or solid-state switching is feasible. The characteristics of an example of each is given in Table IV-6-1. It is recommended that FET switches be used because of size, power consumption and direct logic compatibility. The higher "on" resistance of the FET switch is small compared to the impedances being switched or being switched into. The advantages of FET switches are given in Table IV-6-1.

Various circuit techniques can be used to modify the amplifier's gain and bandwidth. Table IV-6-2 lists some of these methods. Since the GPA is a differential input amplifier with a single-ended output, it is necessary to convert from a differential signal to a single-ended signal somewhere in the circuit. Operational amplifiers are excellent for this purpose. They also provide exceptionally stable gain blocks whose gain and frequency response can be varied very predictably by varying external passive components.

Lead switching can be accomplished by swtiching either the inputs to a single amplifier or by switching to the output of one amplifier for each lead configuration. It is obvious that output switching pays the penalty of requiring many amplifiers to perform a single measurement, but it does remove many of the problems associated with electrical swtiching at low signal levels. FET switches are presently being used to switch ECG leads and even though no information has been uncovered where these switches have been used for

EEG, it is assumed that preamplifiers or buffers will be used, removing any objection to input switching for this sensitive measurement.

7. Safety Devices (BGLS)

In order to be effective, a current-limiting type safety device such as the BGLS must be placed in series with any source of lethal voltage and the subject. The most obvious danger area is the ground lead used for making the bio-potential measurements; however, all leads attached to the subject provide a potential path for lethal currents. Placing these current-limiting devices in series with the inputs to any amplifier used for bio-potential measurements causes the following problems:

1) The source impedance is increased by the insertion impedance of the device with consequent effect on gain accuracy and noise.
2) Any mismatch in insertion impedance from device to device looks like source unbalance to the amplifier and results in degradation of CMRR.
3) The increasing insertion impedance as a function of input voltage will cause some degradation in gain linearity.

Problems 1 and 2 can be alleviated using buffers with the safety device in series with the buffer input. Problem 3 can be ignored at the signal levels in question (10 uv to 5 mv).

8. Buffering

The amplifier requirements discussed previously have been based on a direct electrode/transducer interface and the interposition of other devices has not been considered. By buffering we imply that the source of the signal is isolated from the device making the measurement. Buffers may be single-ended or differential. They may be simply impedance conversion devices

GAIN	(1)	CHANGE OPERATIONAL AMPLIFIER FEEDBACK RESISTOR
	(2)	CHANGE OPERATIONAL AMPLIFIER INPUT RESISTOR
	(3)	SWITCHED DIVIDER NETWORK.
BANDWIDTH		
LOW FREQUENCY	(1)	CHANGE COUPLING CIRCUITS BETWEEN STAGES
HIGH FREQUENCY	(2)	CHANGE OPERATIONAL AMPLIFIER FEEDBACK CAPACITOR

TABLE IV-6-2. CIRCUIT SWITCHING TECHNIQUES

	RELAY	FET SWITCH (SIMILAR TO SILICONIX DG141L)
OPERATING POWER	> 20 MW	< 5MW
LOGIC COMPATIBLE	NO (SPECIAL LOGIC DRIVERS CAN BE USED)	YES
OPERATING TIME	> 1 MS	< 10 μSEC
"ON" RESISTANCE	≈ 1 MILLIOHM	< 100 OHMS
SIZE	TO-5 CAN	INTEGRATED CIRCUITS (SEVERAL SWITCHES PER FLATPACK)

TABLE IV- 6-1. CHARACTERISTICS OF TWO SWITCHING DEVICES

with no actual gain (i.e., gain of one) or they may perform an impedance conversion and also have gain. Regardless of their other characteristics, they must provide a high input impedance and a low stable output impedance in order to be useful as electrode buffers. Hence one certain effect of using buffering is to reduce the required input impedance of the GPA to hundreds of kilohms rather than hundreds of megohms. One other advantage immediately derived from using a buffer is the ability to provide more reliable input switching due to the low and constant nature of the switched source.

A single-ended buffer possessing a gain of one will have no effect on the GPA's gain, noise or CMRR requirements. If, however, the buffer has gain, the gain and noise requirements of the GPA can be relaxed accordingly.

Differential buffers will affect all of the GPA's input requirements since in effect they serve as input stages located close to the electrode site. The differential buffer, however, must be committed to an electrode pair or some means of switching must be provided similar to that required for input lead switching with no buffering. As a result there is really little difference in the description or requirements of the two signal conditioning systems: GPA vs. GPA with differential buffers.

It is anticipated that single-ended, gain of one, electrode buffers will be used for more sensitive measurements such as EEG and with dry or insulated electrodes. The use of these buffers allows to reduce the input impedance of the GPA to the level of tens of megohms. This high an input impedance will still be required to swamp out variations in output impedance from buffer to buffer and, more importantly, to allow the GPA to be used

for bio-potential measurements with wet electrodes without buffers.

9. INPUT IMPEDANCE

The input impedance of the GPA must be high enough not to cause unacceptable loading effects nor serious degradation of CMRR in the presence of an unbalanced source. The assumption will be made that the worst case source impedance is presented by a wet electrode, i.e., $\geq$ 40,000 ohms. Hence, for a .1% loading factor, the common mode input impedance must be a minimum of 40 megohms. An input impedance of 40 megohms and an unbalance impedance of 40 kilohms will cause a degradation of CMRR of approximately 30 to 40 db.

V. AMPLIFIER SPECIFICATIONS

In an attempt to further define the GPA, a preliminary specification has been prepared which contains the values for all the parameters of interest. The specifications are as follows:

PRELIMINARY GPA SPECIFICATIONS

ALL SPECIFICATIONS ARE AT 25°C UNLESS OTHERWISE NOTED.

	MIN.	TYPICAL	MAX	UNITS
1. GAIN (See Note 1)	100		$2x10^4$	
Gain Accuracy (See Note 2)		.1		%
2. INPUT IMPEDANCE				
Common Mode	$4X10^7$	10^8		OHMS
Differential	10^6	10^7		OHMS
3. CMRR (DC)	100	120		db
(100 Hz)	80	100		db

	MIN.	TYPICAL	MAX	UNITS
4. FREQUENCY RESPONSE (See Note 3)				
High Frequency (3 db down)	1000		1200	Hz
Low Frequency (3 db down)			DC	Hz
5. NOISE				
.5 to 1000 Hz		5	10	μv p-p
6. INPUT DYNAMIC RANGE (See Note 4)		70		db
7. INPUT CURRENT				
Either Input		.1	1	na
Differential		.01	.1	na
Doubles every 10°C				
8. INPUT VOLTAGE				
Vs. Temperature		5	10	μvolts/°C
Vs. Time		10	100	μvolts/HR

NOTE 1 — The gain must be capable of being electronically switched from 100 to 20,000 in the following steps:

100
200
400
500
1000
2000
4000
5000
10000
20000

NOTE 2 -- Gain accuracy is to be maintained with a source impedance of 40,000 ohms.

NOTE 3 -- The overall desired bandwidth is DC to 1000 Hz. The following minimum number of upper and lower frequency limits should be provided via electronic switching:

Upper Limit (3 db)	Lower Limit (3 db)
100 Hz	DC Hz
500 Hz	.14 Hz
1000 Hz	.5 Hz

Upper and lower roll-off rates must be a minimum of 10 db/octave.

NOTE 4 -- 10 μv to 25 mv.

VI. DEDICATED VS. GPA TRADE STUDIES

For the purpose of performing trade studies to determine whether a general purpose amplifier approach or a dedicated amplifier approach is best for use in IMBLMS, it is necessary to define a physiological measurements baseline. The baseline measures have been adapted from the IMBLMS Phase C Preliminary Statement of Work dated 5/5/71. The baseline measurements are as follows:

1. EEG 8 Channels
2. EMG 2 Channels
3. EOG 4 Channels
4. VCG 3 Channels
5. ECG 6 Channels

Therefore, there are 5 dedicated amplifier designs to be considered. We will assume that 1 GPA will replace 1 dedicated amplifier, although in actual usage fewer GPA's will probably be required depending upon the manner in which the actual measurements are performed. The trade-off to be considered therefore is between 5 different dedicated amplifier designs in

varying numbers and 23 GPAs.

1. Complexity

From a design point of view, the GPA must be at least as complex as the most sophisticated dedicated amplifier it is to replace but, in addition, it must also provide for switching of frequency and gain. The increased complexity can be represented fairly well as the addition of approximately 12 resistors, 12 capacitors and 4 flatpacks containing 4 FET switches each.

Table VI-1-1 lists the major differences between the amplifiers under consideration. This Table will allow us to assign a rough complexity factor to the designs. Normalizing EOG as 1.0 since it would be the simplest design, we can assign numbers to the other designs as listed in Table VI-1-2.

EOG	1.0
EEG	1.2
EMG	1.3
ECG	1.3
VCG	1.3
GPA	1.5

TABLE VI-1-2 COMPLEXITY FACTORS

Due to similarities in the design of the various amplifier, there would be a learning curve associated with the actual cost of designing the five dedicated amplifiers. See the trade study on cost included in this report.

EOG	SPECIFICATIONS SIMILAR TO GPA – GAIN OF 1000 – NO INPUT SWITCHING REQUIRED – BANDPASS .14 TO 100 HZ.
EEG	SAME AS EOG, BUT GAIN OF 20,000 – LOW NOISE
EMG	SAME AS EEG, BUT BANDPASS OF .5 TO 1000 HZ.
ECG	SAME AS EOG, EXCEPT INPUT SWITCHING AND BANDPASS CAPABILITY TO 500 HZ
VCG	SAME AS ECG, EXCEPT FOR INPUT NETWORK.
GPA	SAME AS EEG, EXCEPT BANDPASS DC TO 1000 HZ, INPUT NETWORKS FOR ECG AND VCG, AND MUST PROVIDE SWITCHING FOR GAIN AND BANDPASS.

TABLE VI-1-1 AMPLIFIER SIMILARITIES

2. RELIABILITY, MAINTAINABILITY AND FLEXIBILITY

It is extremely difficult, in the absence of a specific design, to assess the influence of a GPA versus dedicated amplifier approach on either reliability or maintainability. However, some general comments can be made.

First, due to the increased complexity of the GPA design, it is anticipated that the reliability of the GPA as a component must be less than any single dedicated amplifier.

Secondly, if reliability also contains a factor depending on ultimate mission success (i.e., completion of desired experiments), then the absolute interchangeability of the individual GPAs must increase this factor.

Thirdly, maintainability on a component repair basis must be decreased in the GPA approach due to sheer increase in parts counts and circuit complexity.

Fourth, system maintainability in terms of getting the system back up after an amplifier failure should be unaffected regardless of which amplifier approach is used. In the case, however, of a limiting spares situation, interchangeability will provide a quicker turn-around time than component repair.

Since ach GPA channel is to be capable of performing ECG, VCG, etc., although certain channels, based on experiment design, will be ear-marked for particular measurements, it will be possible to increase the number of channels of any particular measurement at will, up to the number of GPAs in the system. Thus, in our hypothetical system, there could be up to 23

channels of EMG available should a deviation in experiment results deem them necessary. This means greater measurement flexibility in the overall system flexibility. Table VI-2-1 summarizes the above.

	GPA	DEDICATED
COMPONENT RELIABILITY	−	+
MISSION SUCCESS	+	−
COMPONENT MAINTAINABILITY	−	+
SYSTEM MAINTAINABILITY	+	−
FLEXIBILITY	+	−

TABLE VI-2-1

3. COST

In order to prepare an effective cost trade-off for the GPA, it is necessary to delineate between recurring and non-recurring costs. For the purposes of this trade, non-recurring costs are as follows:

a. Engineering Design

b. Planning

c. Tooling/Set-Up

d. Training

e. Qualification

f. Material/Vendor NRE

Recurring costs are as follows:

a. Manufacturing

b. Quality Control

c. Engineering Follow-Up

d. Material

Table VI-3-1 gives a matrix of non-recurring costs for 10 similar designs. Based on an estimated $10,000 engineering effort for the first design. The engineering effort for succeeding designs decreases based on the similarity of the designs.

Table VI-3-2 gives a cross tabulation of recurring charges for a single design versus the number of units built.

Table VI-3-3 gives a cross tabulation of recurring charges for 5 designs versus total number of units built.

In all cases, the engineering costs for a single design have been normalized at $10,000.

We can now arrive at a relative cost factor for each approach. For the dedicated amplifier approach, we have 23 units of 5 different designs. Looking at Table VI-3-1, we have a non-recurring cost of $65,908 and from Table VI-3-3, we have a recurring cost of $44,302, for a total of $110,310. In the case of the GPA, we have a non-recurring cost of $23,580 and a recurring cost of $30,900 (Table VI-3-2), for a total cost of $54,480. Hence, the cost ratio between the two approaches is 2:1.

SINGLE AND MULTIPLE DESIGN -- TABULAR -- NON-RECURRING DESIGNS

	1	2	3	4	5	6	7	8	9	10	CURVE
PLANNING	480	336	297	274	258	246	237	229	222	216	85%
TOOLING/SETUP	500	250	202	176	158	145	135	127	121	115	75%
TRAINING	600	300	242	211	190	174	162	152	145	138	75%
QUALIFICATION	10000	6000	5060	4530	4180	3910	3710	3540	3400	3280	80%
MATERIAL/VENDOR NRE	2000	1200	1012	906	836	782	742	708	680	656	80%
ENGINEERING	10000	5000	4040	3510	3160	2900	2700	2540	2410	2300	75%
TOTAL	23580	13086	10853	9607	8782	8157	7686	7296	6978	6705	
CUMULATIVE	23580	36666	47519	57126	65908	74065	81751	89047	96025	102730	

TABLE VI-3-1 SINGLE AND MULTIPLE DESIGN -- TABULAR -- NON-RECURRING DESIGNS

TABLE VI-3-2 RECURRING UNIT COST (1) DESIGN

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
MFG.	1200	840	742	685	646	616	592	572	556	541	529	517	508	498	490	482	476	469	463	457	452	446	442	438	433	430
Q.C.	600	420	376	342	323	303	296	286	278	270	264	258	254	249	245	241	238	234	232	228	226	223	221	219	216	215
ENG.	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
MAT.	300	300	300	300	300	300	300	300	300	300	270	270	270	270	270	270	270	270	270	270	250	250	250	250	250	250
TOTAL	2300	1760	1618	1527	1469	1419	1412	1358	1334	1311	1263	1245	1232	1217	1205	1193	1184	1173	1165	1155	1128	1119	1113	1107	1099	1095
CUM.	2300	4060	5678	7205	8674	10093	11505	12863	14197	15508	16771	18016	19248	20465	21670	22846	24047	25220	26385	27540	28668	29787	30900	32007	33106	34201

TABLE VI-3-3 RECURRING UNIT COST -- 5 DESIGNS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
MFG.	1200	1080	1038	1013	994	979	967	956	948	940	934	926	921	916	911	907	902	899	895	892	888	884	882	880	877	874
Q. C.	600	540	519	506	497	489	482	478	474	470	467	463	460	458	455	453	450	449	447	446	444	442	441	440	438	437
ENG.	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
MAT.	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
TOTAL	2300	2120	2057	2019	1991	1968	1949	1934	1922	1910	1901	1889	1881	1874	1866	1860	1852	1848	1842	1838	1832	1826	1823	1820	1811	1811
CUM.		4420	6477	8496	10487	12455	14404	16338	18260	20170	22071	23960	25841	27715	29581	31441	33293	35141	36983	38821	40653	42479	44302	46122	47933	49744

VII. RECOMMENDATIONS

The recommendations of this study are as follows:

(1) For intended flight applications a single amplifier design with a single qualification program and redundancy in manufacturing and operability is the most effective approach to be taken.

(2) The amplifier must be designed to have a differential input with a sufficiently high input impedance to allow it to be used with chosen transducers and conventional wet electrodes.

(3) The amplifier must have sufficient input switching to allow for the various lead combinations required for a clinical ECG.

(4) Gain and frequency adjustment will be switched and will provide for a minimum of 5 selectable gains for each measurement.

(5) Switching will be accomplished using integrated circuit J-FET switches compatible with TTL logic.

(6) Buffers should be used to pre-process the signals received by the amplifier. These buffers will be either located at the electrode site or as close thereto as conveniently possible. For a dedicated amplifier system buffers would also provide optimum performance. The GPA will have the capability of operating without buffers with degraded performance in noise and CMRR.

GENERAL ELECTRIC

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