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FINAL REPORT

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DEVELOPMENT OF BLOOD PRESSURE MONITOR (Arterial Wave Velocity Meter)

(NASA CR-53392)

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CONTROL AIL DIVISION

Dec~~ember~~ 1962

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SUMMARY

An eleven month project is described which has resulted in delivery to Ames Research Center of an instrument for the continuous monitoring of propagation velocity of externally impressed, transverse, arterial waves as defined by Landowne and others. The equipment measures propagation velocity by timing the passage of a superimposed acoustic wave over a known length of artery. Constants have been chosen such that approximately some 210 discrete determinations of velocity are made within the normal heart pulse cycle; therefore detailed intra-pulse information is available.

The purpose of developing this equipment has been to provide a new tool for cardiovascular research, and therefore a serious attempt has been made to avoid similarity to any instrument already known to have been developed. The resulting equipment will, hopefully, make the analysis of certain circulatory phenomena easier and more meaningful.

The design has been made with a view to providing for quick and easy application to various human subjects, and also to providing for relatively comfortable wearing of the device while engaged in normal physical activity. Wire leads must, however, be attached to the equipment which is worn.

Encouraging and consistent results have been obtained during limited trials of the device, and indications are that a very sensitive indicator of circulatory reactions to

environment has been produced. Consequently, some recommendations are made in respect to future work with this concept.

Because there were conceptual modifications made during the execution of the project, a short discussion of the changing project philosophy has been included in the introductory material.

II. INTRODUCTION

The original proposal, made by A.I.L. and accepted by Ames Research Center, was for an instrument which would measure maximum and minimum transverse wave velocities (during the heart cycle) and convert them into numbers which might, after suitable clinical trials, be correlated with the familiar systolic and diastolic blood pressures. Such a proposal, at the time of formulation, seemed useful and adequate in view of the strong and widespread need at the time for automated, non-occlusive blood pressure information.

Before the actual project was well underway, however, certain important facts emerged:

A. The urgent need for non-occlusive systolic-diastolic blood pressure meters was somewhat reduced by the appearance of operational prototype instruments developed by others.

B. There came to be a considerable interest in the use of wave propagation velocity as a useful diagnostic tool per se.

C. The interest in obtaining detailed and continuous information, within the heart pulse cycle, about instantaneous arterial condition became quite widespread.

D. Early experiments pointed toward the fact that instantaneous impressed wave velocity may well be a sensitive function of other factors besides instantaneous blood pressure.

These changes in atmosphere, then, made it seem highly likely that a more useful instrument could be developed if it

were to provide continuous information correlatable with instantaneous propagation velocity than if it were to provide periodic information which might be related to the more familiar blood pressure readings. Accordingly, but with due allowance for being able to deliver the proposed instrument in the unlikely event of failure of the modified concept, the design concept was changed.

The project work description shows that the project broke down into five more-or-less distinct phases, representing an approximate chronological statement of project effort:

Phase I - the gathering and/or designing of equipment with which to test and implement the proposal.

Phase II - The proving out of the proposed scheme as a potential source of useful measurements.

Phase III - The assessment of preliminary results and the decision to substitute continuous read-out of wave velocity for max.-min. determinations.

Phase IV - The redesign of circuitry and methods for the revised goals.

Phase V - The construction of deliverable equipment which would be reasonably well adapted to Ames Research Center requirements.

Each of the phases, of course, was a moderately complex aggregate of related activities. The following outline of major points covered in the description of work may prove helpful.

PHASE I - Initial Design Phase

A. Choice of measurement schemes.

B. Vibrator development.

C. Microphone development.

D. Determination of suitable energy levels and spectra.

E. Use of "artificial artery."

PHASE II - Validation Phase

A. Comparison of measurements made in various body locations.

B. Comparison of measurement on various body types.

C. Comparison of computed with measured values.

D. Collection and correlation of data relating velocity to blood pressure.

E. Comparison of "up-stream" and "down-stream" results in wrist-forearm region.

Phase III - Change of Goals Phase

A. Acquired information from other developments.

B. Expanding interest in wave velocity per se.

C. Expanding interest in continuous, intra-pulse behavior.

D. Experimental feedback from the project work.

1. Wave velocity depends upon factors other than blood pressure.

2. Wave velocity is a sensitive indicator of, and is rapidly responsive to, circulatory change.

3. Increased resolution is possible with two-microphone scheme.

4. Improvement in performance is obtainable from C-W equipment.

PHASE IV - Re-development Phase

A. Development of paired-microphone technique.

B. Reversal of vibrator-microphone locations.

C. Redesign of circuitry and elimination of pulsed energy.

D. Collection of patient trial data.

PHASE V - Final Construction Phase

A. Determination of Ames Research Center requirements.

B. "Convenience" design for vibrator.

C. "Isolation from ambient" design for microphones.

D. Packaging for centrifuge usage.

III. DESCRIPTION OF WORK

PHASE I - Initial Design

The project began with an investigation into the most suitable methods of measurement of transmission velocity for impressed transverse arterial waves. Two techniques were followed extensively, 1) the pulsed energy technique and 2) the continuous wave technique. The first method consists of applying a train of short duration mechanical pulses to the artery and measuring the actual time for these pulses to travel a known distance. The second technique consists of impressing a continuous sinusoidal wave on the artery and measuring the phase change across a known distance. Breadboard systems were assembled and used to compare the two techniques.

Preliminary tests quickly showed that a vibrator capable of emitting several watts of acoustic energy over a considerable range of frequencies would be required for breadboard work, so an electromagnetic unit of convenient size and shape (shown in figure 1) was constructed. Ceramic microphone units were found to be useful to receiving this energy, and consequently the microphone construction problem was one of adapration and providing suitable electronic preamplification.

It was found that attenuation of an impressed wave as it travelled down the artery limited the microphone-to-vibrator distance to 12 cm or less on the radial artery. The best

repetition rate of the pulsed energy was found to be approximately 30 pulses per second. Similarly the optimum frequency of an impressed sine wave, in the continuous wave technique, was found to be approximately 300 cycles per second. Each of these determinations was, of course, a compromise between transducer performance, signal attenuation in the arterial system, and data resolution capability.

The block diagram of the pulsed energy breadboard system is shown in figure 1. Time measurements were made by observing the time delay on a two channel oscilloscope. Transit time was successively measured over two distances; thus making the results independent of time delays present in the system at points other than the radial artery itself.

The block diagram of the continuous wave breadboard system is shown in figure 2. In such a system, of course, phase relationship between periodic waves can be equated to time shifts whenever the frequency of the waves is known. If the transmission distance between the launched and received energy points is also known, the velocity of transmission can then be calculated. By measuring phase shift when the vibrator and microphone are separated by distance D_1 and again by distance D_2 the non-pertinent phase shifts, in parts of the system other than the radial artery, are ignored. The velocity V can then be expressed as:

$$V = \frac{K(D_1 - D_2)}{\phi_1 - \phi_2}$$

where k = conversion constant

ϕ_1 = total system phase shift with separation distance between microphone and vibrator, D_1

ϕ_2 = total system phase shift with separation distance, D_2

In order to have an easily controlled and unvarying "subject" on which to make early measurements, the "artificial artery" of figure 4 was constructed. This thin-walled rubber tube labarynth system served as a sort of ca ibrating unit on which results could be roughly checked against theory. Later on, this was to demonstrate dramatically the difference between the propagation characteristics of ideal elastic tubes and living arteries (see Phase II).

PHASE II - Validation Phase

One formidable problem of the early work on this project was that of making certain that the time delays observed in experimentation were caused by propagation velocity in the artery and not simply by characteristics of the instrumentation system. For example, it is quite possible to postulate that the phase shifts observed might be manifestations of variable coupling between the artery wall and the transducers - which coupling should, of course, vary during the heart cycle in accordance with local artery distension.

Such a theory, once postulated, is indeed difficult to disprove.

Lacking the funding and/or time allowances for building an expensive and intricate measuring system with dynamic linearity sufficient to handle a then-unknown measurement range, we elected to use the indirect approach. Thus, we were able to show:

1. That the equipment gave results roughly agreeing with theory for both the artificial artery and for live subjects, in spite of the fact that propagation velocity is inversely related to pressure for the one as compared with the other (1) (2).

2. Velocity measurements made on segments of different-sized arteries (carotid, subclavical, brachial and radial) seemed to show rough agreement with published values.

3. Measurements made on radial artery segments in various body types ("deep" and "surface" blood vessels as well as "muscular" and "fatty" tissue) seemed to give comparable results.

4. Good correlation between sphygmomanometer pressures and propagation velocities for some fifteen subjects.

5. Excellent comparison of data taken on the forearm regardless of whether the impressed wave was launched at the pulse palpation point (surface) and picked up from the mid-arm (deep), or vice-versa.

Figure 9 shows a spread of maximum impressed wave velocity vs. systolic pressure for 10 subjects measured by two techniques at A.I.L. Blood pressure was measured by sphygomomanometer. The pulsed-energy readings were taken with separation distances of 2 and 4 inches between vibrator and microphone. The vibrator frequency was 30 cps. The continuous-wave data were taken with a 300 cps "carrier." The average subject age was approximately 30 years. As can be seen, some of these data were obtained before the equipment had been well worked over and therefore the spread is rather large. Nevertheless, the correlation between blood pressure and propagation velocity seems unmistakable.

r (systolic pressure, velocity at systole) = 0.74

PHASE III - Change of Goals

As pointed out in the Introduction, there was some interest apparent in the early part of the project for a continuous wave-velocity device, as opposed to a max.-min. type of blood pressure device. The circumstance which dramatically demonstrated the value of such an alternative, however, was the indication from some of our breadboard work that a great deal of valuable intra-pulse information was being ignored in attempting to provide a systolic-diastolic blood-pressure readouts. Realization that a two-microphone readout would be required for accuracy in the presence of ambient noise or muscular disturbances, further

increased the amount of detail available from a continuous read-out.

Inasmuch as continuous intra-pulse velocity information could be obtained with good resolution it was felt that this data should be preserved in lieu of obtaining only a maximum and minimum reading corresponding to systole and diastole. Furthermore, since impressed wave velocity seemed to depend upon arterial conditions other than intraluminal pressure, it seemed that propagation velocity itself might better be the output. Such velocity could, of course, be related to pressure by the user if desired, so that the case for change-over then seemed clear. Samples of the sort of information available from a continuous reading system is shown in Figures 12 and 13.

PHASE IV - Re-Development

Because of the greater signal-to-noise ratio achievable with the continuous wave technique as well as the ease of obtaining continuous intra-pulse impressed wave velocity information, the pulsed energy technique was finally discarded in favor of the c-w method. Figure 9 is a block diagram of the final deliverable system. Two microphones, separated by 2 inches over the radial artery, each detect the arrival of the impressed waves. By measuring the difference in phase as the waves arrive at the two microphones, all extraneous phase shifts in the system are neglected.

With the need for a two-microphone technique, came the need for an acoustically isolated pair of microphones held at a fixed distance from each other and yet easily attached to the subject's arm. The result, based upon ceramic microphone units, is that shown in figure 13. Details of construction are shown in figure 14.

The vibrator has been mounted distal to the microphones to permit better coupling of the vibrator into the radial artery. This technique was found to be useful in improving the signal-to-noise ratio attainable with the c-w system, since by providing rather direct coupling to the radial artery (at the pulse palpation point on the wrist) the amount of extraneous signal induced into tissue surrounding the artery is greatly reduced.

PHASE V - Final Construction Phase

It was determined that there were some specialized requirements involved in using this equipment at Ames Research Laboratory. These requirements seemed to be basically three:

(1) The output to be recorded should range between 0 and +1 volt, and should work into a 10,000 ohm load.

(2) All equipment should either fit on the centrifuge chair or go out to a fixed environment through the slip ring assembly. Electrical noise is such that these rings should be used at a level of 1/3 volt or above.

(3) Because of the presence of a guide rail for the centrifugal assembly, the acoustical environment is aptly described as "noisy."

Accordingly, extra isolation material was added to the microphone assembly and a preamplifier unit was arranged for mounting on the chair.

Figures 9 thru 11 and 14 thru 19, then, represent parts of the equipment as delivered. Speaking descriptively, there are three electrically connected equipment locations:

(1) The subject wears, by means of Velcro straps about the forearm, a vibrator, a microphone pair, and wires for bringing in power and taking out data signals. These wires terminate in the preamp unit. Figure 18, is illustrative of this.

(2) The chair contains a preamplifying unit whose principal function is to raise the level of the individual microphone outputs to the order of 1 volt. Additionally, this unit serves as a junction box for supplying power to the subjects' vibrator unit. Spade-lug terminals are provided on the slip ring cables. This unit is shown in Figure 10.

(3) The main equipment unit of the system is shown in Figure 16 and is intended to be mounted conveniently remote from the subject. The circuitry and equipment contained here is that which schematically occupies the left-hand dotted-line enclosure of Figure 19.

The equipment should be used with a recording unit (for the output signal display) and an oscilloscope (for input monitor and output monitor display). These latter are provided for convenience in setting up the system and

assuring that the arm transducers are properly located upon the subject. When the system is in operation, the monitors have no direct usage as data suppliers, although their displays will no doubt provide confidence in the results. For purposes of making a proper double-beam oscilloscopic display, the trigger signal has been brought out for a synchronizing pulse.

Basic operating instructions are included under EQUIPMENT DETAILS.

A necessary and important part of any optimization procedure is a so-called clinical evaluation of the equipment in essentially its final form. Although it had been originally planned to do this after the deliverable equipment had been completed, revised scheduling caused by the change-of-goals activity necessitated making a considerable number of these trials with the final breadboard equipment. Consequently, subjects were commandeered more or less at random from within the laboratory, beginning in September, and subjected to test. In all, nearly 25 subjects were tested and the results obtained were cause for an appreciable amount of re-design activity for the transducers.

IV. CONCLUSIONS AND RECOMMENDATIONS

It is thought that the project described above has provided a hitherto unavailable tool for use in cardiovascular research. Preliminary results obtained with the equipment in the laboratory of the developer point to rapid and sensitive indications of relatively minor changes in circulatory conditions when caused by exercise, reorientation of the body, change in breathing rate, and the like.

It is also thought that the required equipment and circuitry are basically simple enough to make for a relatively practical instrument. Power levels are thought to be presently low enough to avoid discomfort or interference with activity on the part of the subject, and could be reduced further. Mechanical design of transducers, while probably adequate for initial research work, can, and should, be improved later. One would look forward to a future version which is no more of a restriction to the subject than wearing a pair of wrist watches plus a thin cable attachment to his surroundings.

Experience with the equipment to date would suggest that the equipment be used to gather sizeable quantities of subject data covering such points as:

(a) ease of application to various body types

(b) intra-subject reproducability of results

(c) relation of output to instantaneous blood pressure (on a per-patient basis)

(d) relation of output to other patient factors

(e) correlation of the details of the output waveform with pathological condition of subject.

(f) reliability of equipment

(g) preferred form for the equipment and for the output display

For acquiring such experience it is recommended that additional models of the equipment be constructed and subjected to test under as wide a variety of conditions as possible. Certain project-generated ideas already exist with respect to improving usefulness of this device for research activities. No doubt field experience will quickly uncover further ideas, and all should be considered for inclusion in subsequent units. Eventually, no doubt, one would want to include a simple computation network to allow results to be read out in medically informative terms.

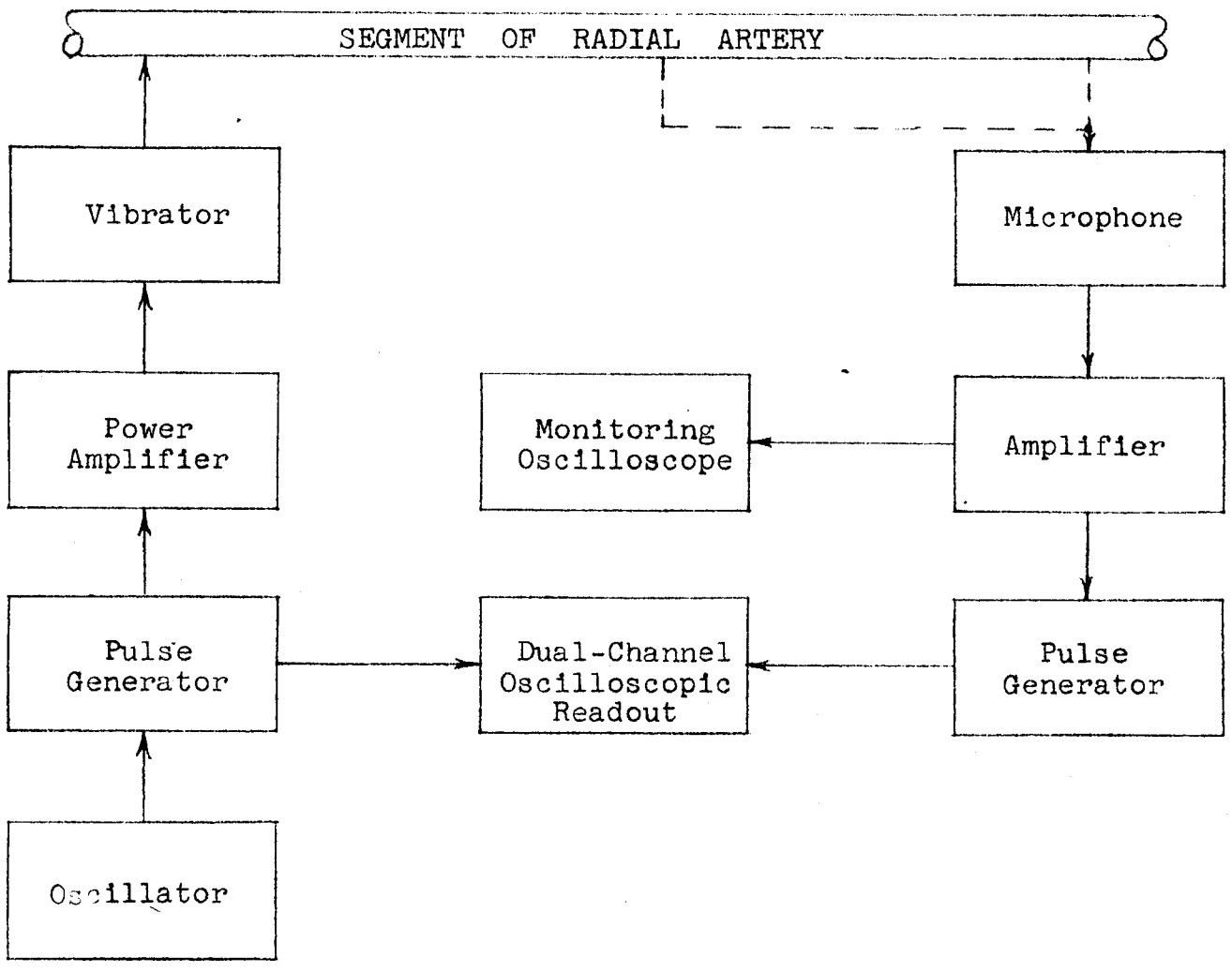


FIGURE 1 - BLOCK DIAGRAM FOR BREADBOARD OF PULSED-ENERGY MEASURING SYSTEM

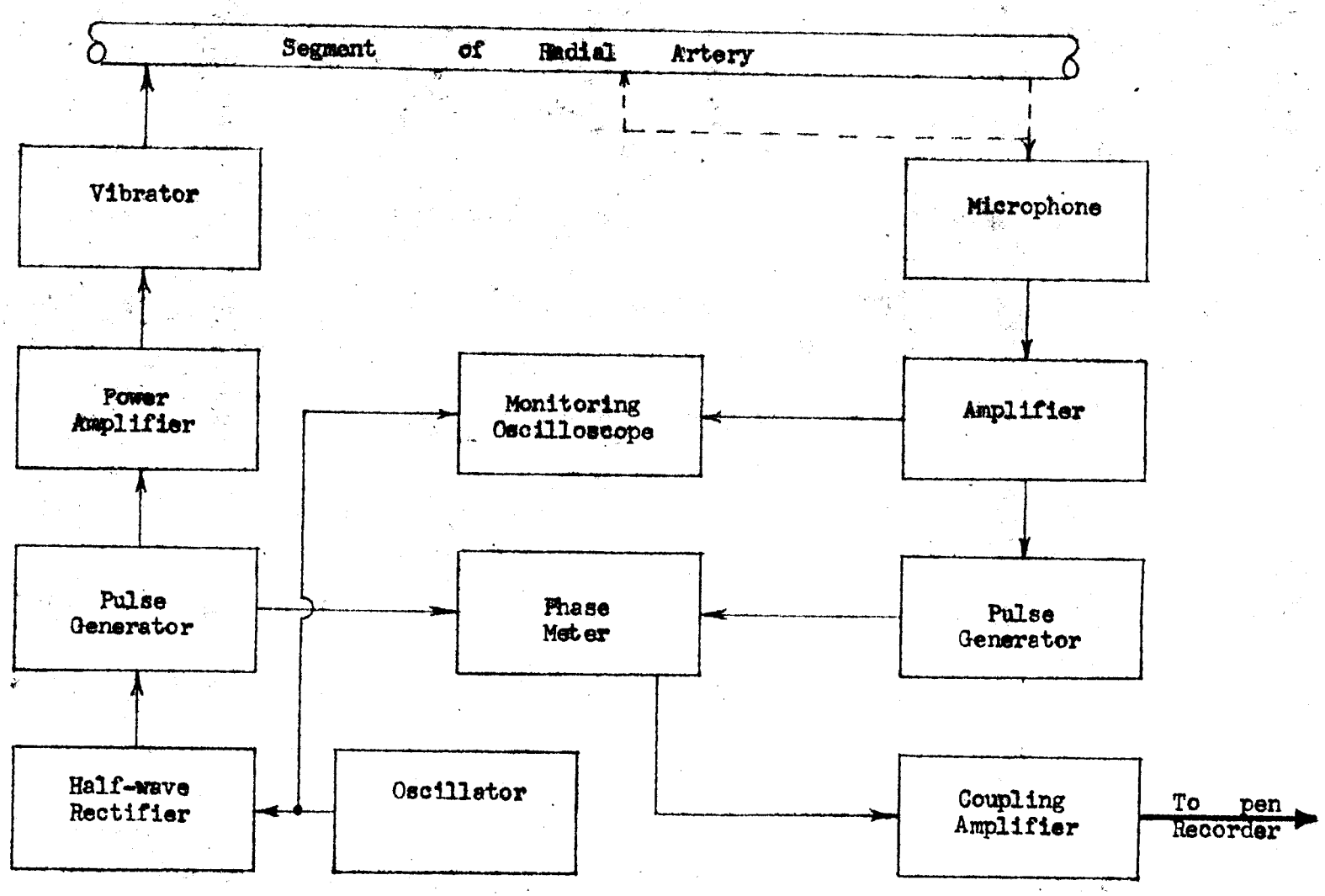
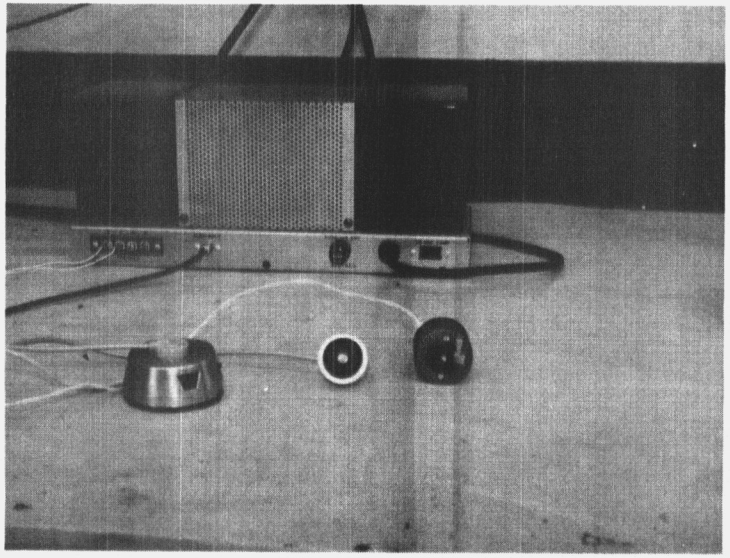
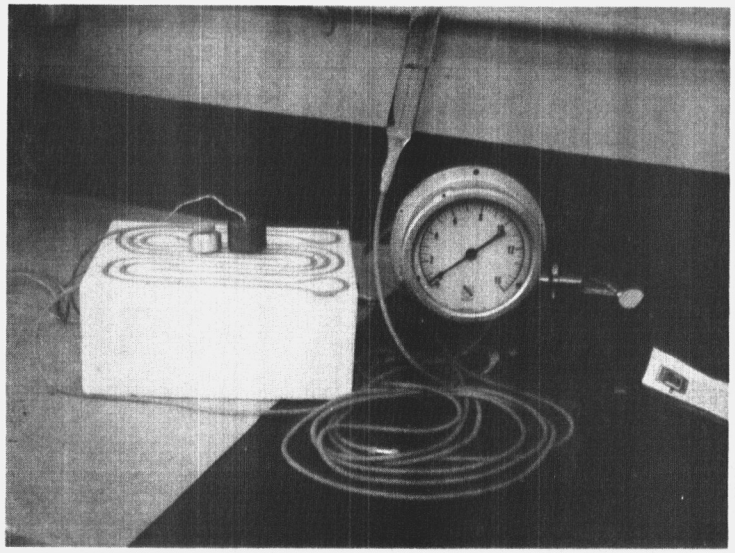


FIGURE 2 - BLOCK DIAGRAM FOR BREADBOARD OF CONTINUOUS-WAVE MEASURING SYSTEM



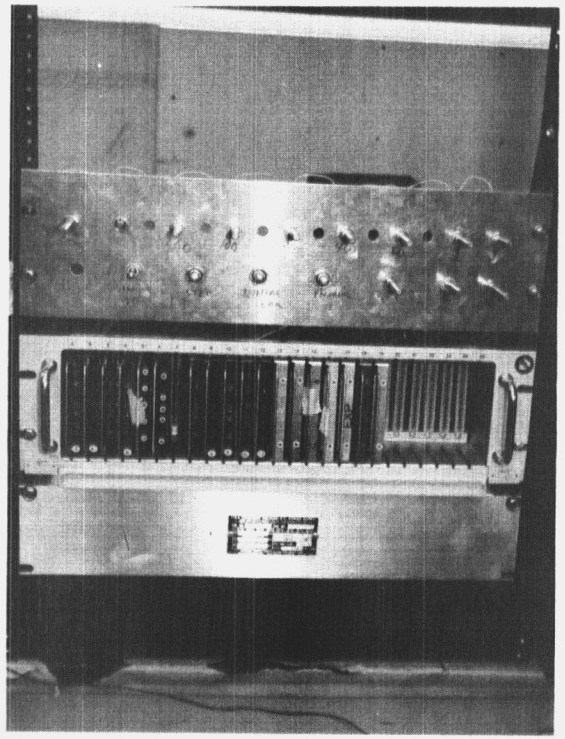
VIBRATOR AND MICROPHONE USED FOR BREADBOARD STUDIES

Figure 3



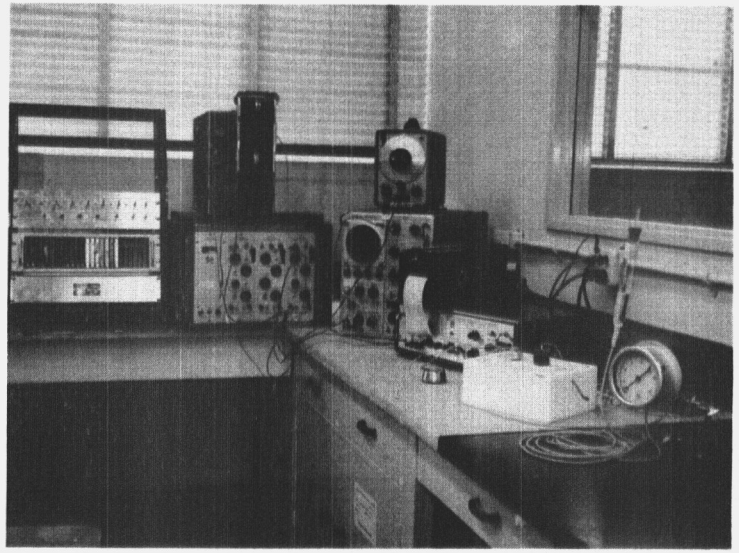
VIBRATOR AND MICROPHONE BEING USED ON
ARTIFICIAL ARTERY IN BREADBOARD TEST PHASE

Figure 4



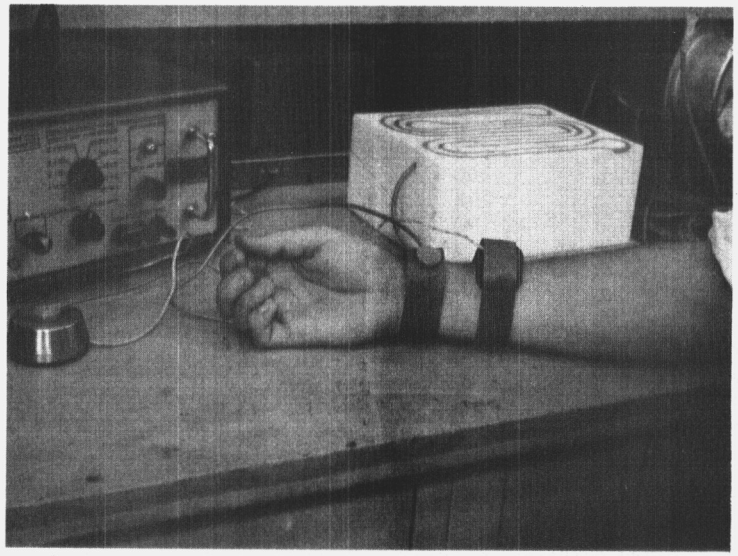
DIGITAL LOGIC ASSEMBLY FOR
USE WITH SYSTEM OF FIGURE 1

Figure 5



COMPLETE BREADBOARD ASSEMBLY FOR BREADBOARD
APPLICATION OF PULSE AND C-W SYSTEMS

Figure 6



VIBRATOR AND MICROPHONE BEING APPLIED
TO LIVE SUBJECT IN BREADBOARD PHASE

Figure 7

K+E 10 X 10 TO THE INCH 359-5
KEUFFEL & ESSER CO. MADE IN U.S.A.

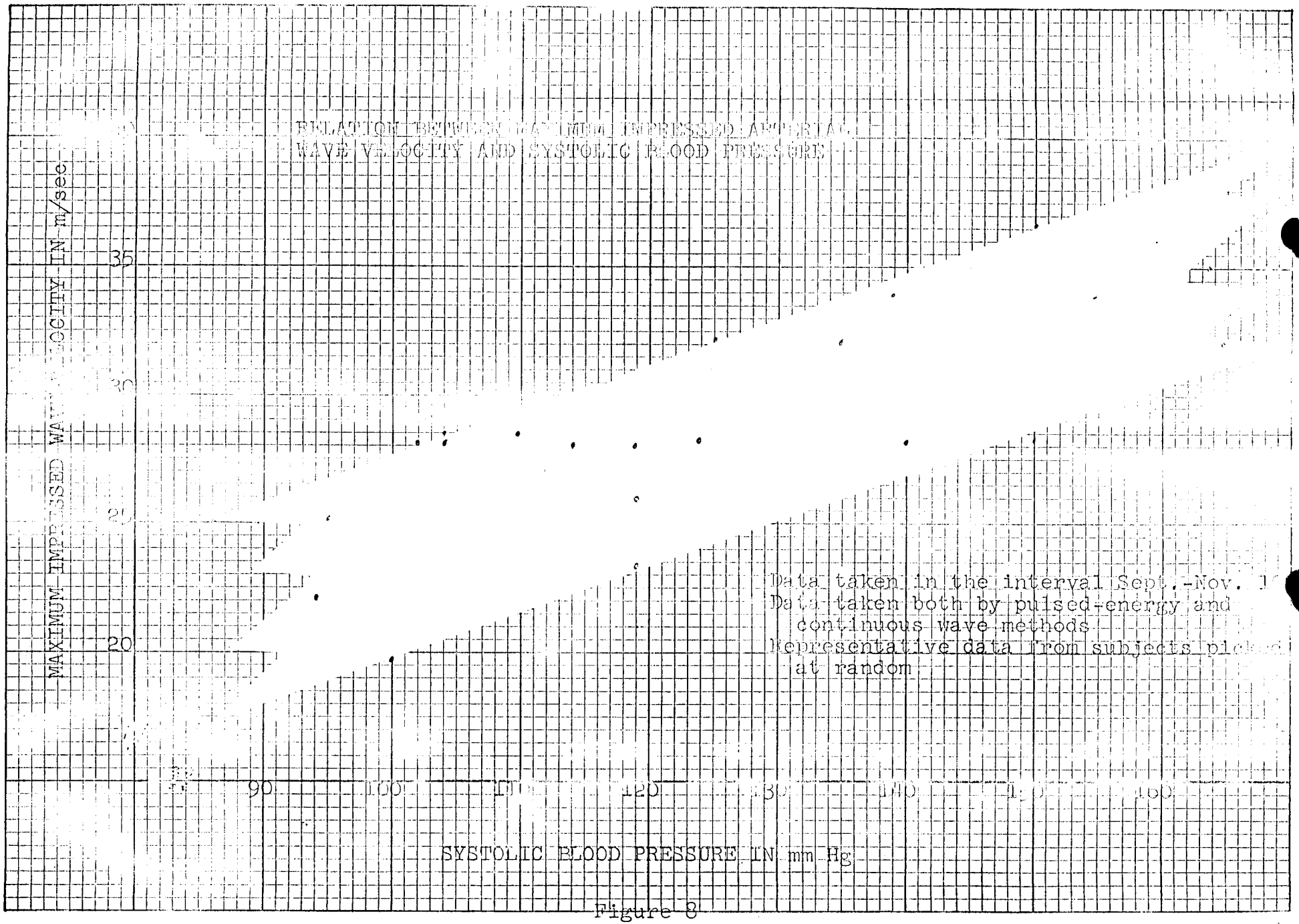


Figure 8

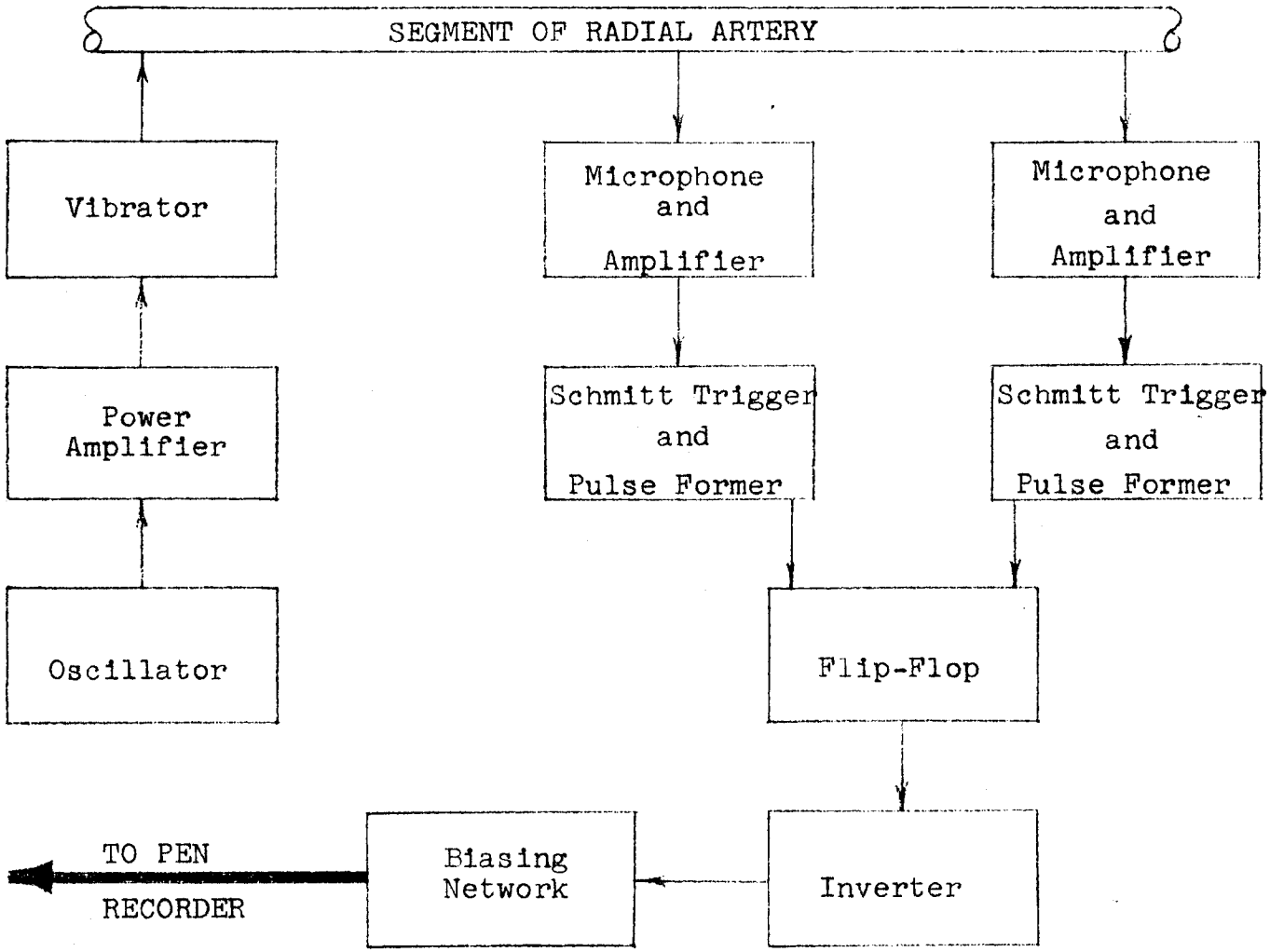
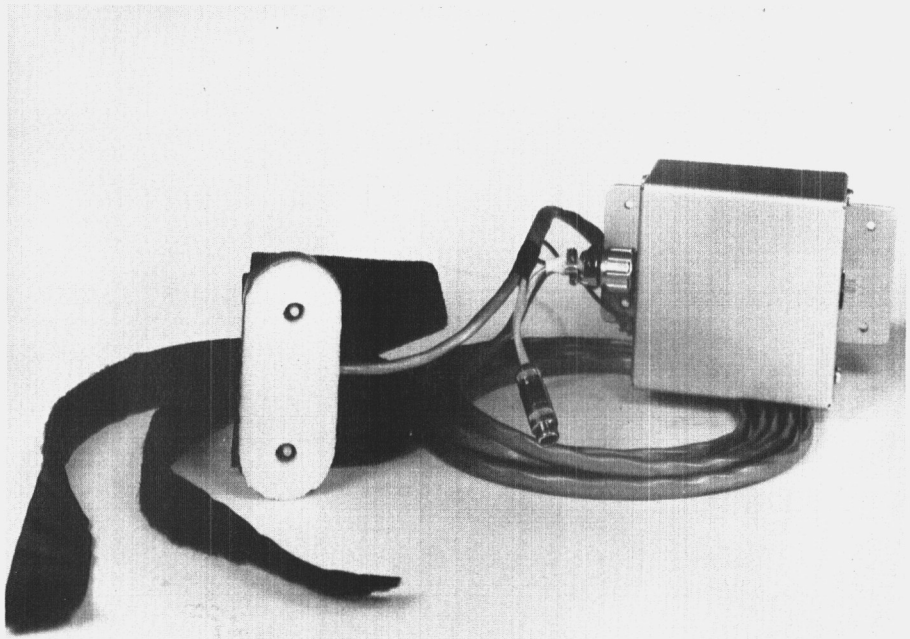
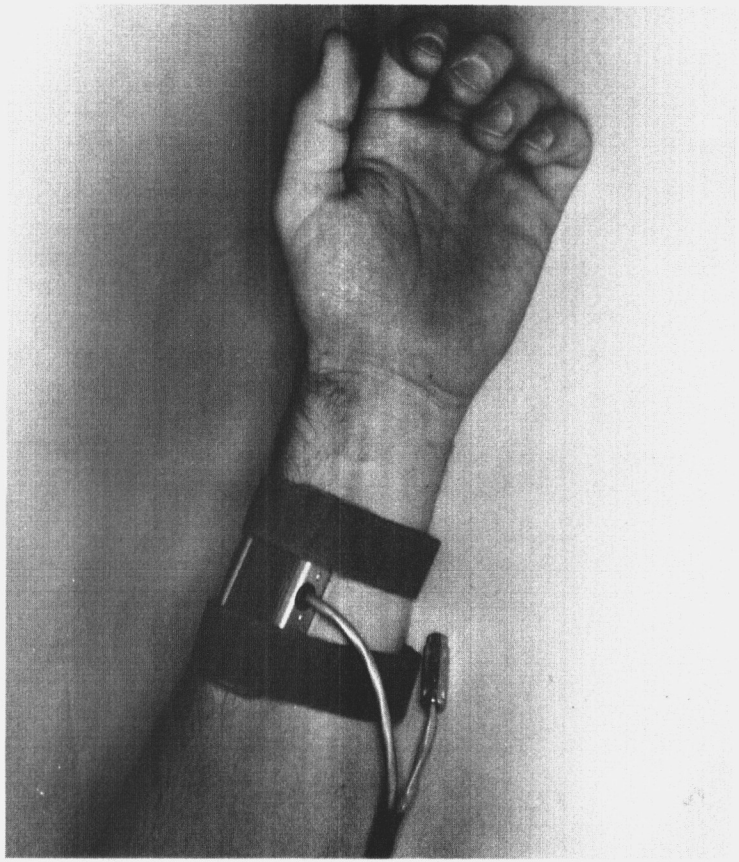


FIGURE 9 - BLOCK DIAGRAM OF FINAL MEASURING SYSTEM

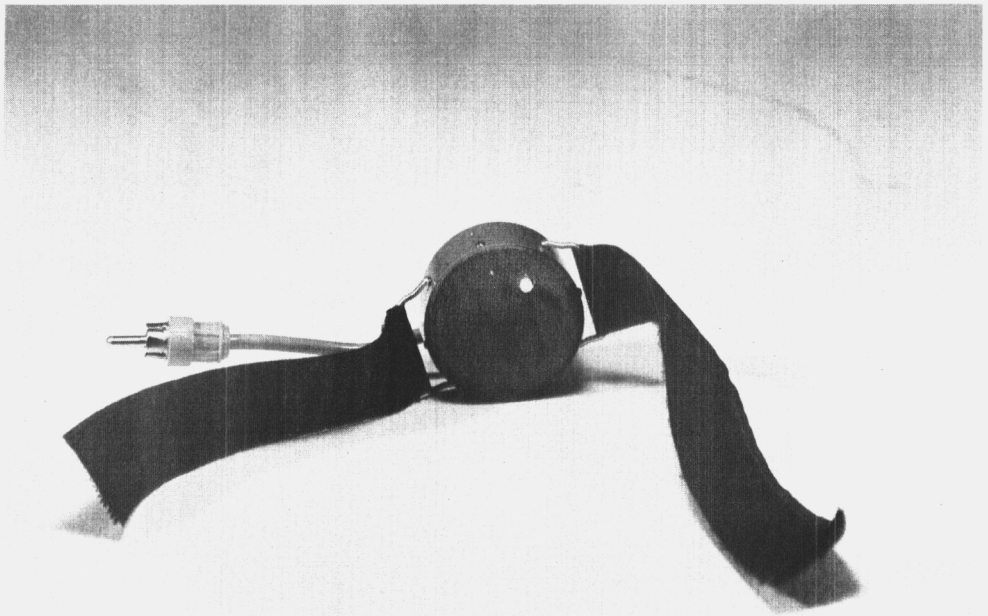


A. EQUIPMENT ASSEMBLY

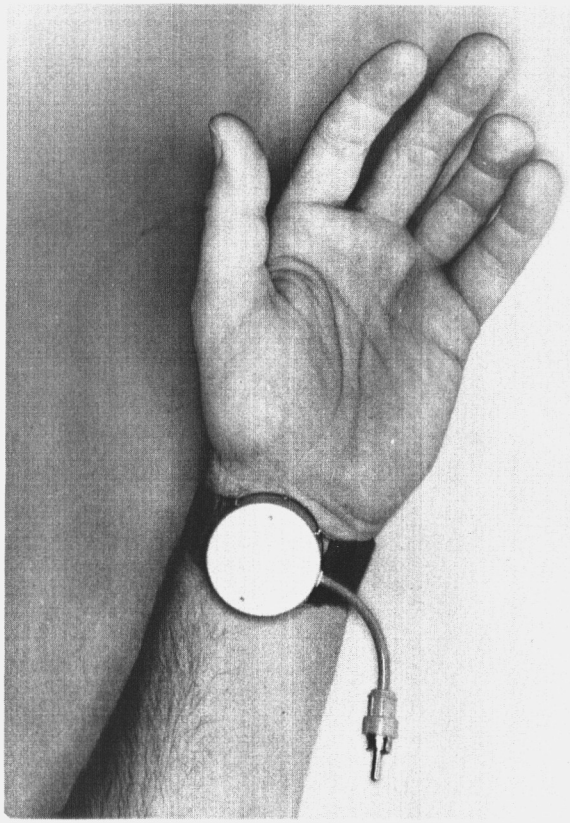


B. PATIENT WEARING MICROPHONES

FIGURE 10. MICROPHONE PAIR AND PREAMPLIFIER USED IN FINAL EQUIPMENT

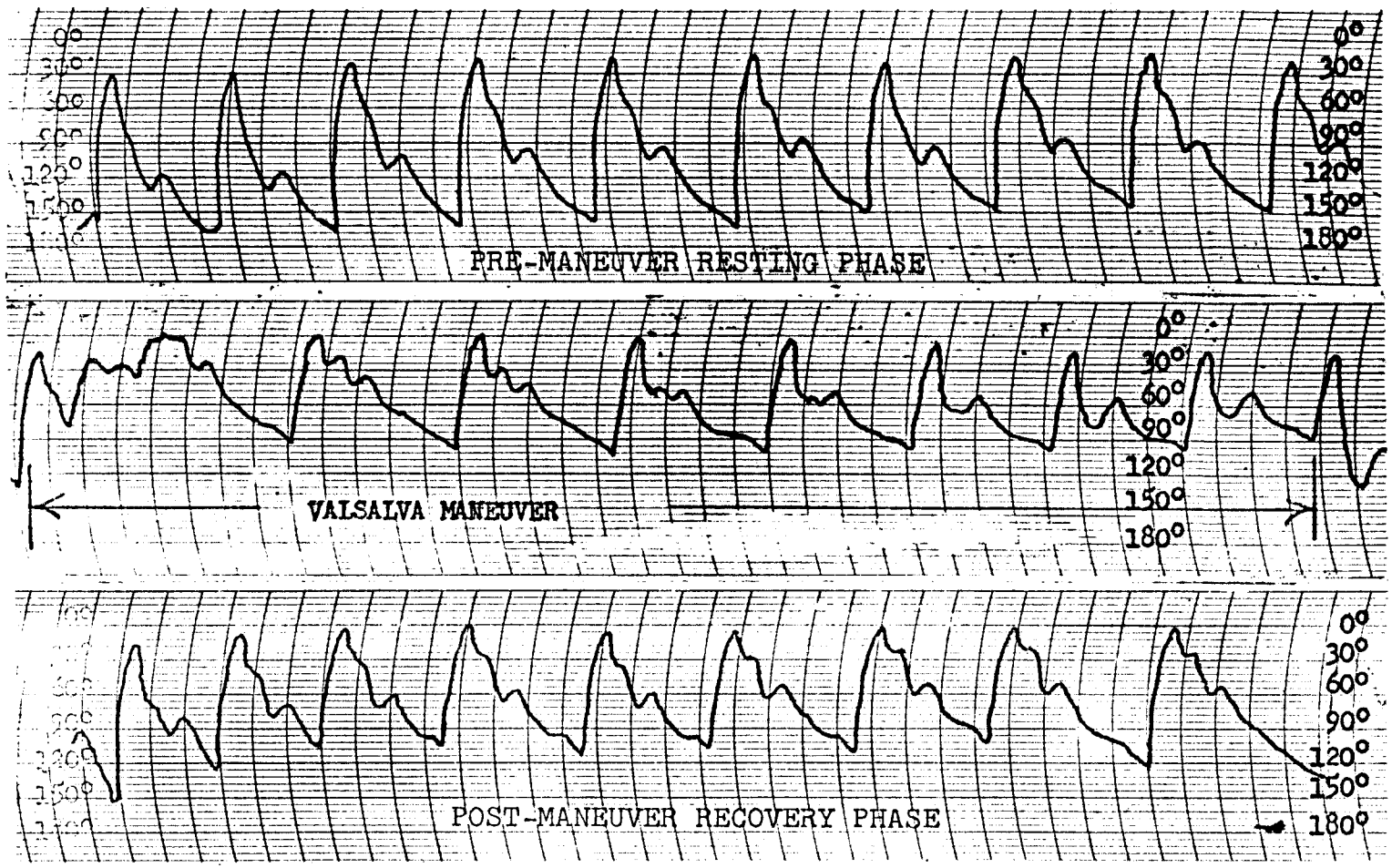


A. VIEW FROM UNDERSIDE



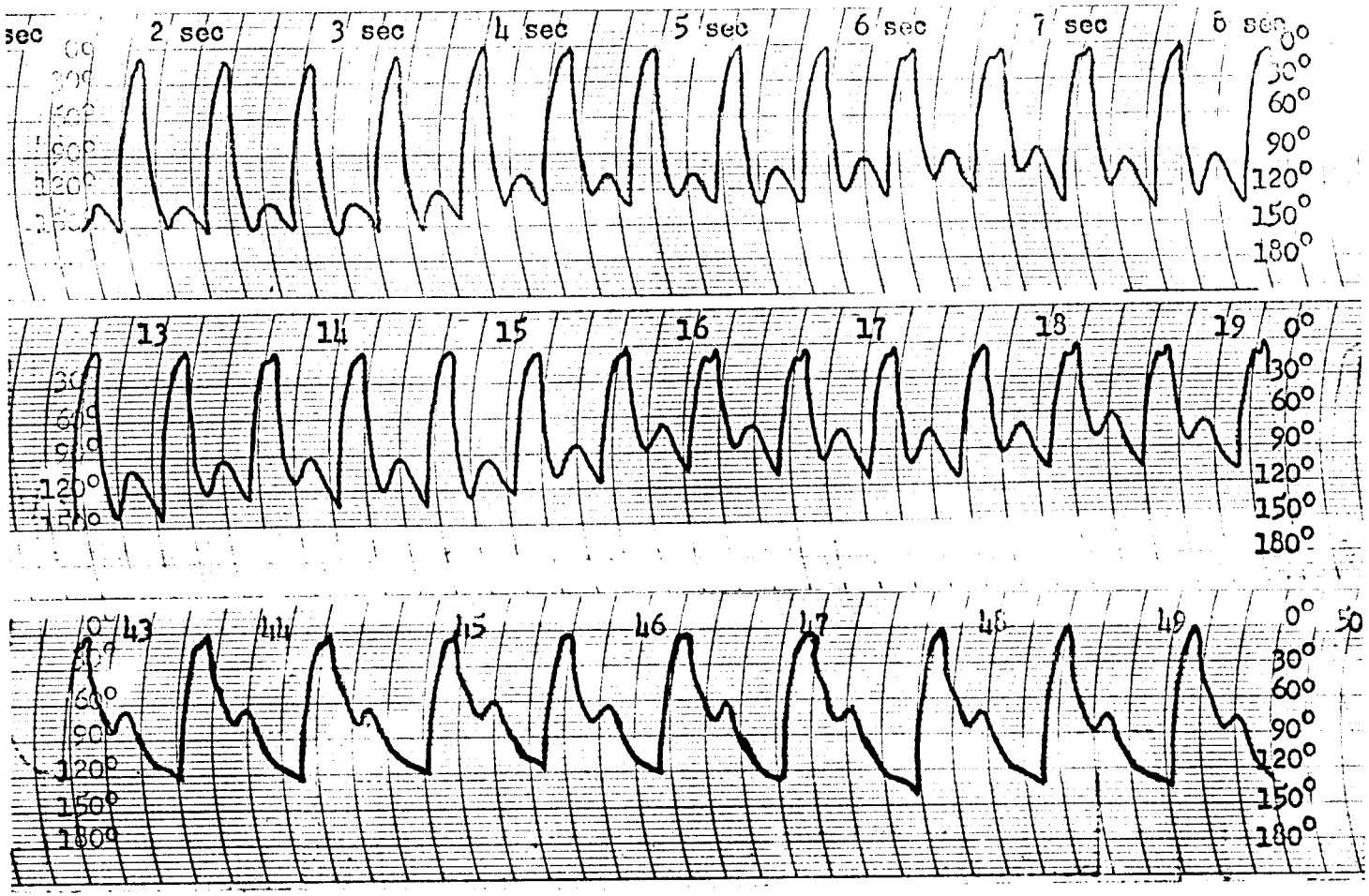
B. VIEW AS APPLIED TO ARM

FIGURE 11. VIBRATOR AS DEVELOPED FOR THE FINAL EQUIPMENT



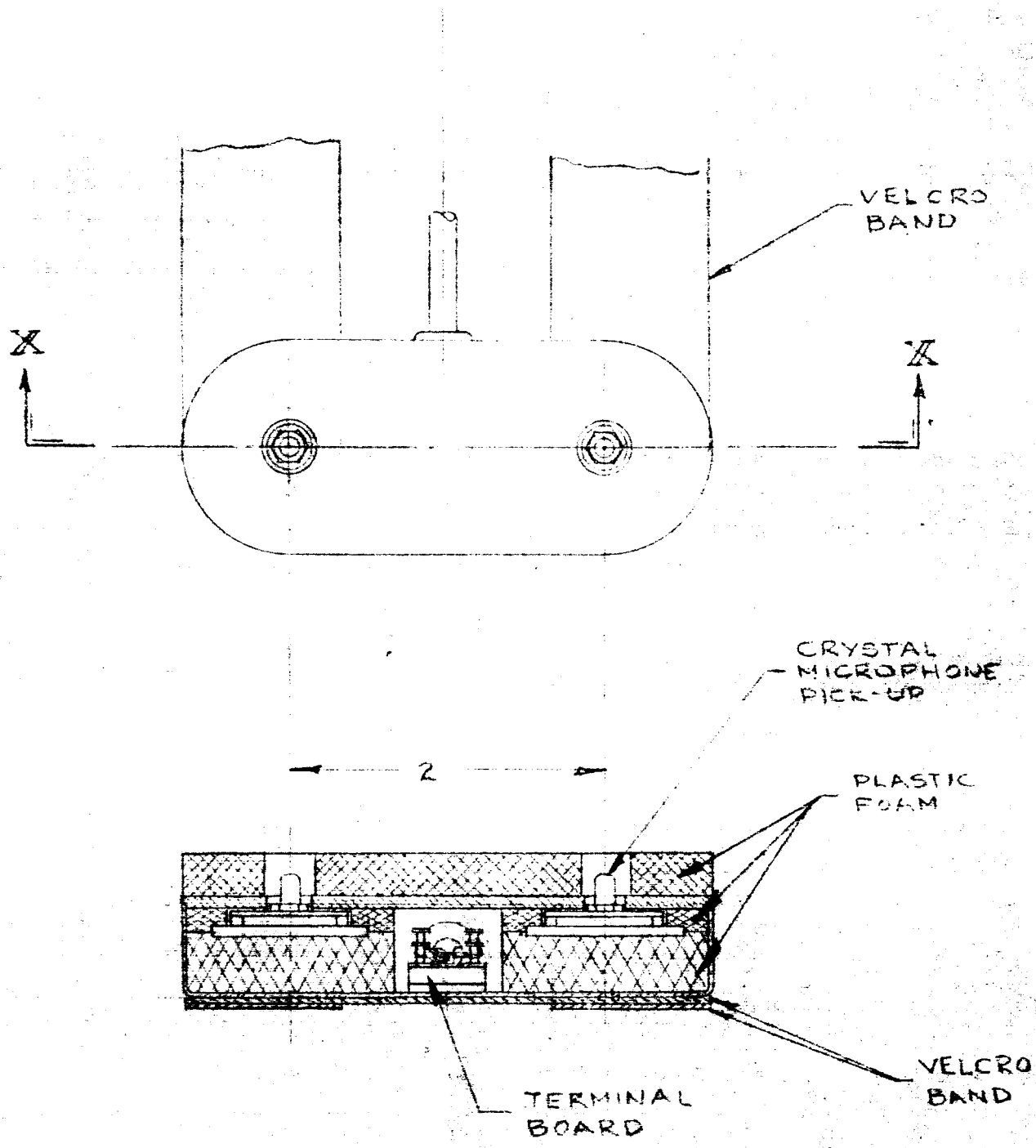
Sections from record taken with continuous-wave breadboard equipment.
Frequency of impressed wave set at 300 cps.
Distance between vibrator and microphone set at 4 inches.
Chart speed set at 5 divisions per second.
To obtain actual phase-shift, add 360° to scaled value.

FIGURE 12 - RECORDED RESPONSE OF TYPICAL SUBJECT TO VALSALVA MANEUVER.



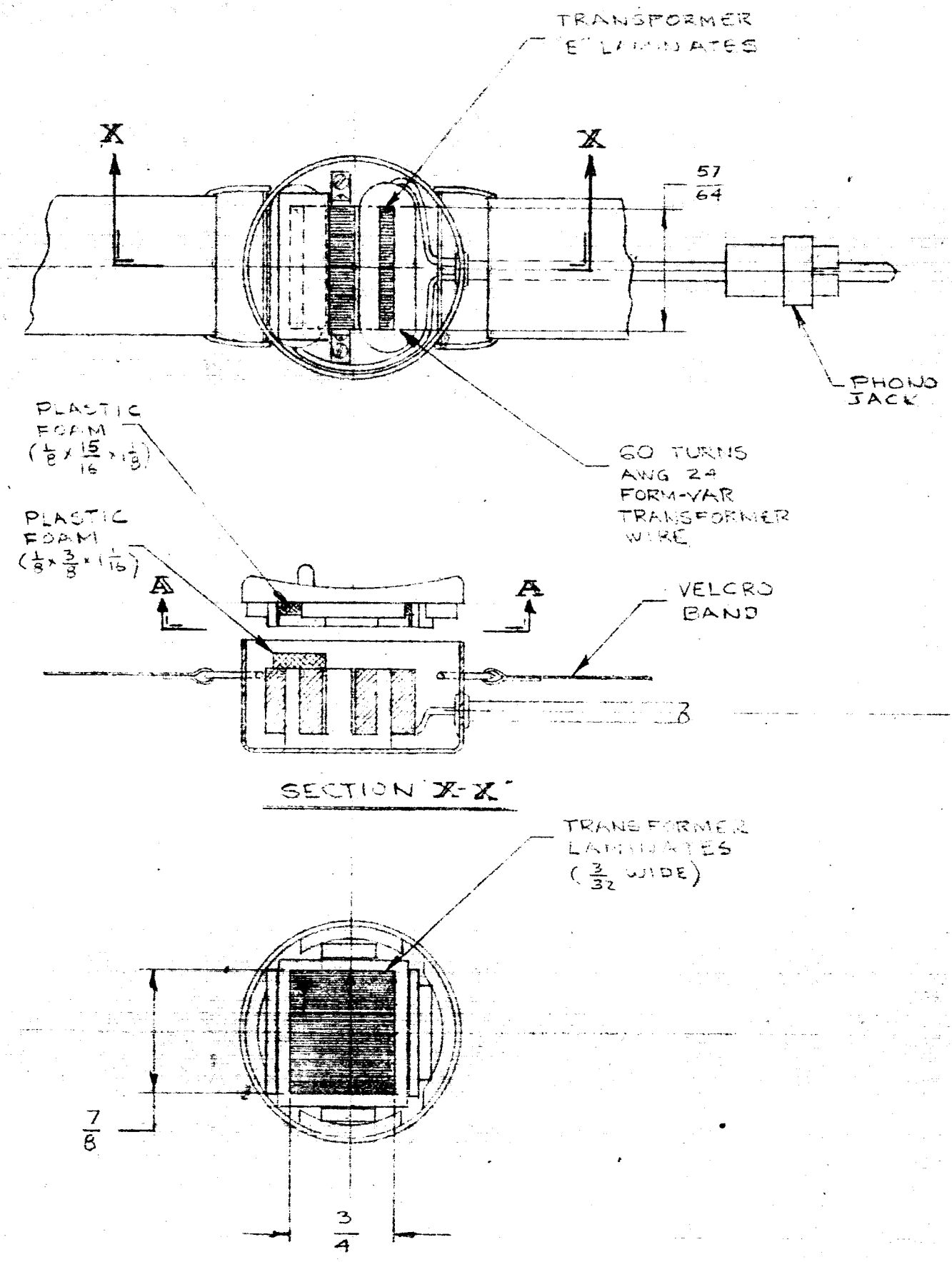
Sections from record taken with continuous-wave breadboard equipment.
Parameters are the same as in Figure 4.
Exercise consisted of 20 deep knee bends, completed just prior to start of time scale.

FIGURE 13 - RECORDING FROM TYPICAL SUBJECT AFTER EXERCISE



MICROPHONE

FIG. 14



VIBRATOR

FIG. 15

FIGURE 16. EXTERIOR VIEW OF MAIN UNIT OF ARTERIAL WAVE VELOCITY MEASURING EQUIPMENT

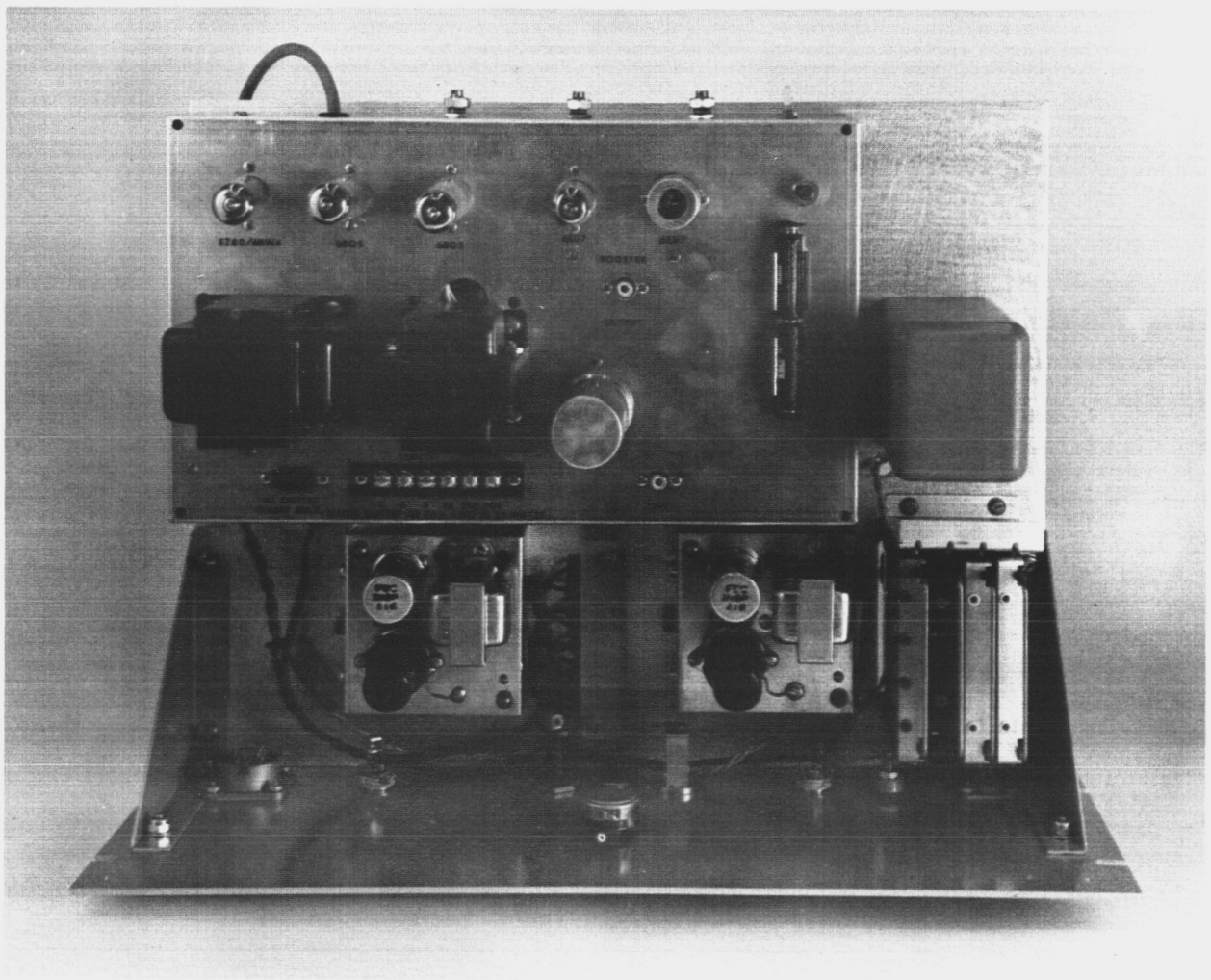


FIGURE 17. INTERIOR VIEW OF MAIN CHASSIS EQUIPMENT

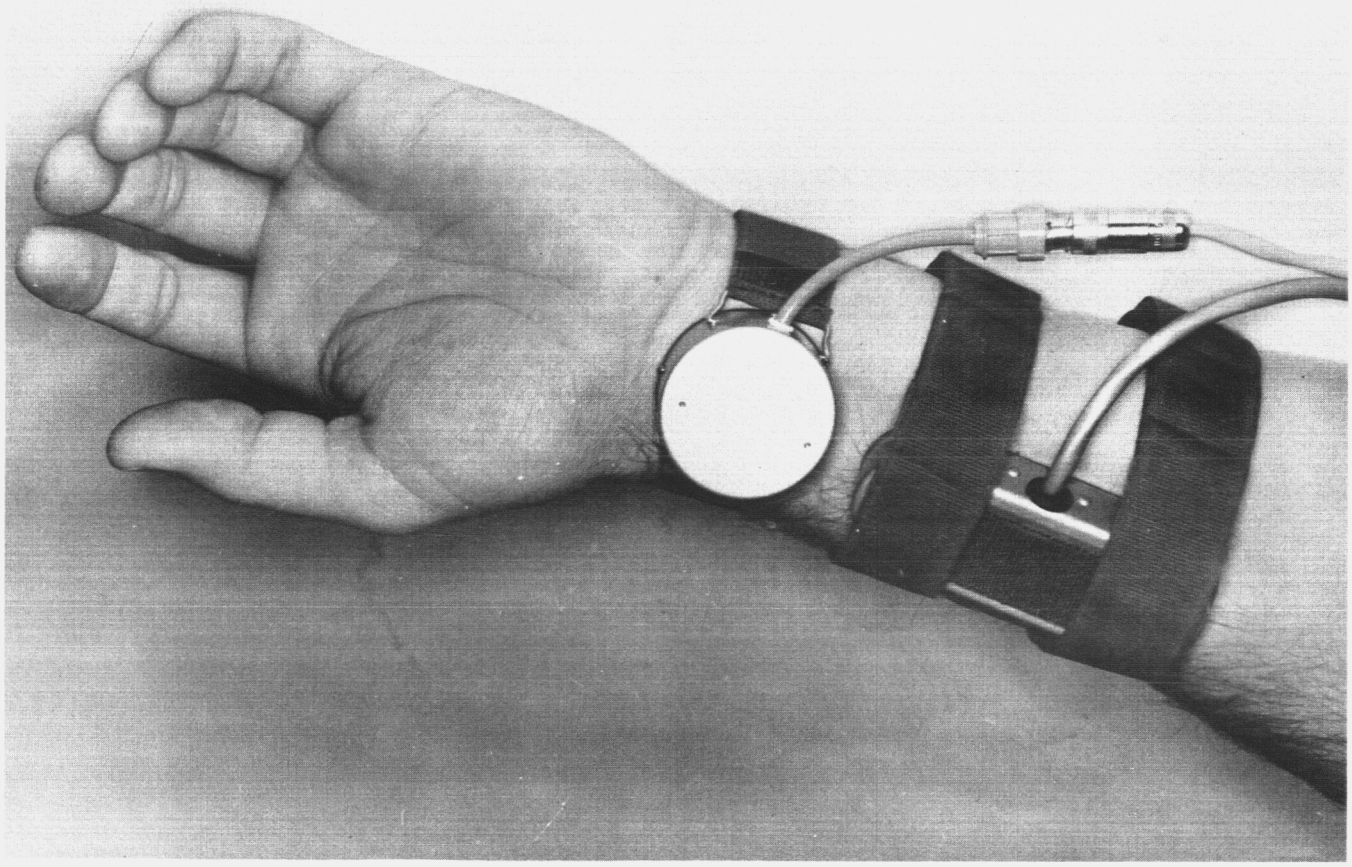
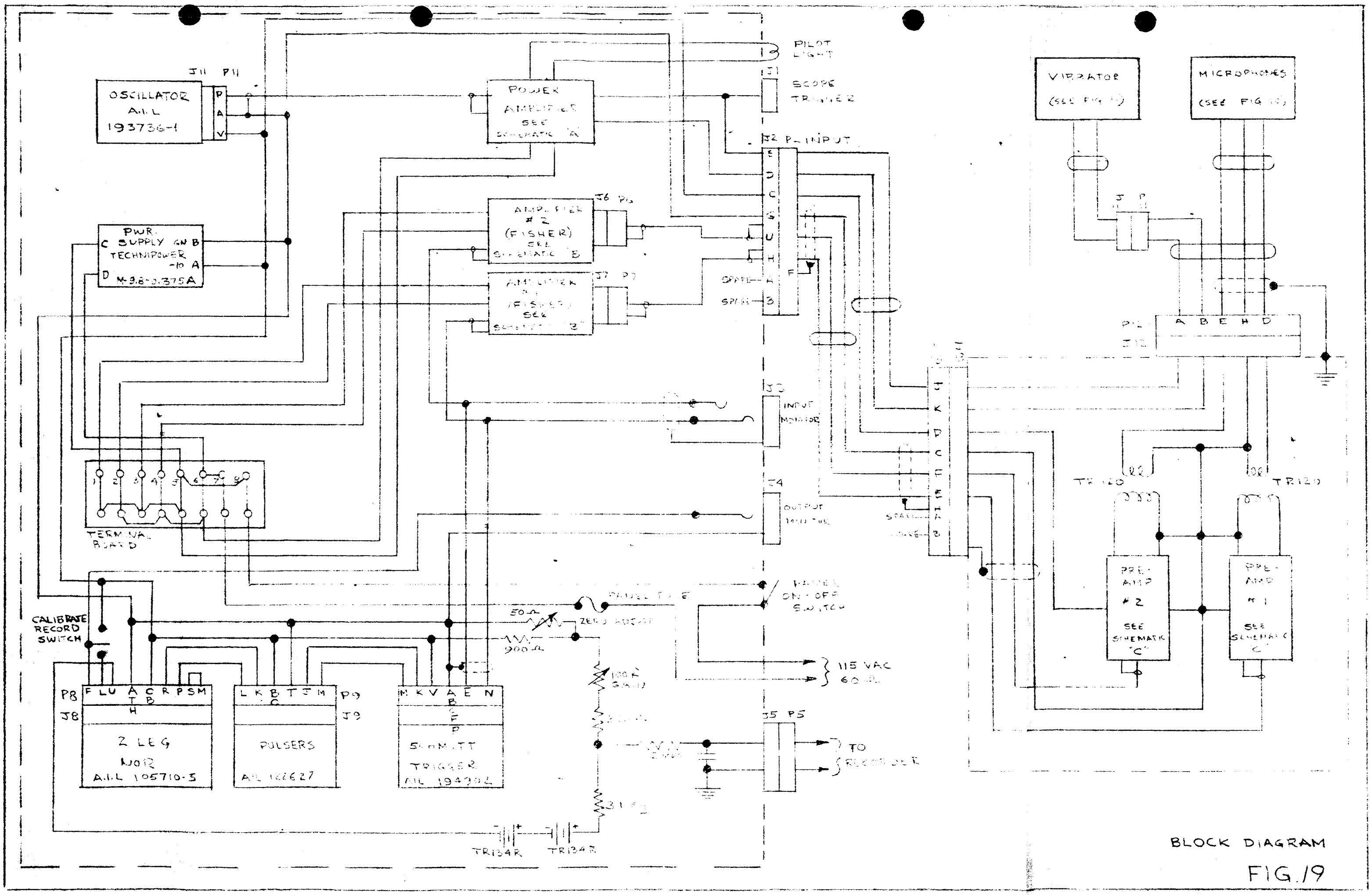


FIGURE 18. EQUIPMENT MOUNTED ON SUBJECT'S ARM FOR TESTING



BLOCK DIAGRAM

FIG. 19

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