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CARDIOVASCULAR EFFECTS OF VIBRATION

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On CARDIOVASCULAR EFFECTS OF VIBRATION

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STUDIES TO DETERMINE THE UNDERLYING MECHANISMS OF SOME CARDIOVASCULAR CHANGES BROUGHT ABOUT BY VIBRATION

INTRODUCTION

Tachycardia, increased $(dp/dt)_{max}$ of left ventricular pressure (LVP), and decreased peripheral vascular resistance observed as early transient changes occurring during vibration of anesthetized dogs were described previously.[1]

By the administration of propranolol and atropine it was established that the tachycardia observed did not result from an increase in sympathetic efferent activity, but from a decrease in vagal efferent activity to the heart. Table I summarizes these results.

Table I. Percentage Change from Non-Vibrating Control Value

Vibration	Heart Rate	Cardiac Output	Total Peripheral Resistance	$(dp/dt)_{max}$ LVP
No Drugs	+47%	+79%	-34%	+20%
After Propranolol	+35%	+40%	-19%	+19%
After Atropine	0	+ 9%	-13%	+ 2%
After Atropine and Propanolol	0	+26%	-19%	+ 6%

It remained to corroborate that changes in $(dp/dt)_{max}$ of LVP did not result from changes in left ventricular end-diastolic pressure.

This point was examined using dogs in which respiratory movement had been abolished by administration of succinylcholine. These dogs were artificially respired between vibration periods using a Harvard respirator. Measurements of heart rate, left ventricular end-diastolic pressure, cardiac output, and $(dp/dt)_{max}$ of LVP were made during apnea and during apnea plus vibration. In order to ensure adequate oxygenation during apnea, the dogs were respired on 100% O_2 for 20 seconds before the pump was stopped. Blood PO_2 and PCO_2 were determined before and after apnea.

RESULTS

Figure 1(a and b) illustrates the cardiovascular changes during vibration in a dog after administration of propranolol. Apart from a slower initial heart rate, these results are in every way similar to those obtained under control conditions before propranolol was given.

Heart rate, cardiac output, $(dp/dt)_{max}$ of LVP, and fluctuations in blood pressure were observed. It is seen that there is no change in left ventricular end-diastolic pressure.

COMMENT

It appears that there is no significant change in left ventricular end-diastolic pressure during vibration. Early transient chronotrope and inotrope are attributed to a decrease in vagal efferent activity and are accompanied by a decrease in peripheral vascular resistance. We cannot exclude positively the possibility that the augmentation in $(dp/dt)_{max}$ of LVP may be secondary to the chronotropism (chronotropic-inotropism).

Origin of the initial stimulus has yet to be determined. Changes in heart rate and blood pressure occur almost simultaneously. The rate of onset of tachycardia after the peripheral resistance is decreased (by decompressing a femoral arteriovenous fistula) begins within a beat or two of the beginning of the pressure drop.[2] If the reflex occurs so rapidly, then tachycardia seen following vibration can well be a reflex response to a decrease in peripheral resistance. The fact that tachycardia of vibration is prevented by atropine, although a change in peripheral resistance still persists, indicates a reflex tachycardia. This indication is further supported by the decrease in heart rate observed after the blood pressure has been restored.

Studies are underway to determine the cause of the decrease in peripheral vascular resistance. Experiments using phentolamine as an alpha adrenergic blocking agent show that a drop in peripheral resistance still occurs despite alpha receptor blockade.

An experiment using phenoxybenzamine as an alpha blocking agent and propranolol as a beta blocking agent showed a decrease in peripheral vascular resistance during vibration, presumably in the presence of complete sympathetic blockade (see Fig. 2).

When this experiment was repeated after a vagolytic dose of atropine was administered a marked fall in blood pressure was seen, again with the usual recovery toward the end of vibration (Fig. 3). With heart rate fixed and sympathetic efferent activity blocked, it is a matter of interesting speculation as to what mechanism is responsible for the restoration of blood pressure. Of course one must first be certain that the various blockades were complete. These experiments are to be repeated and if the

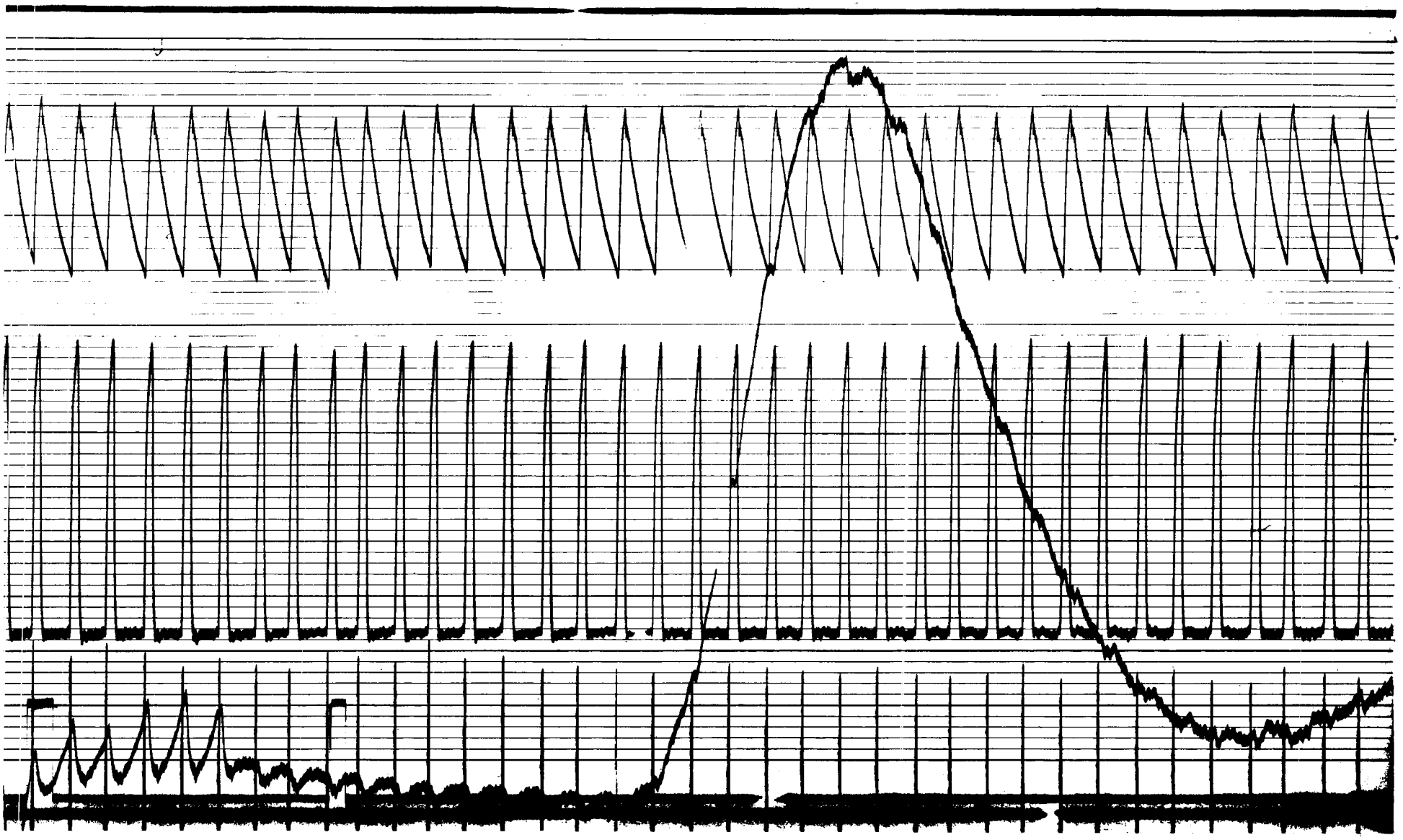


Fig. 1(a) - From top: Thoracic aortic pressure, LVP, $(dp/dt)_{max}$ of LVP. Dye curve superimposed. Apnea after propranolol

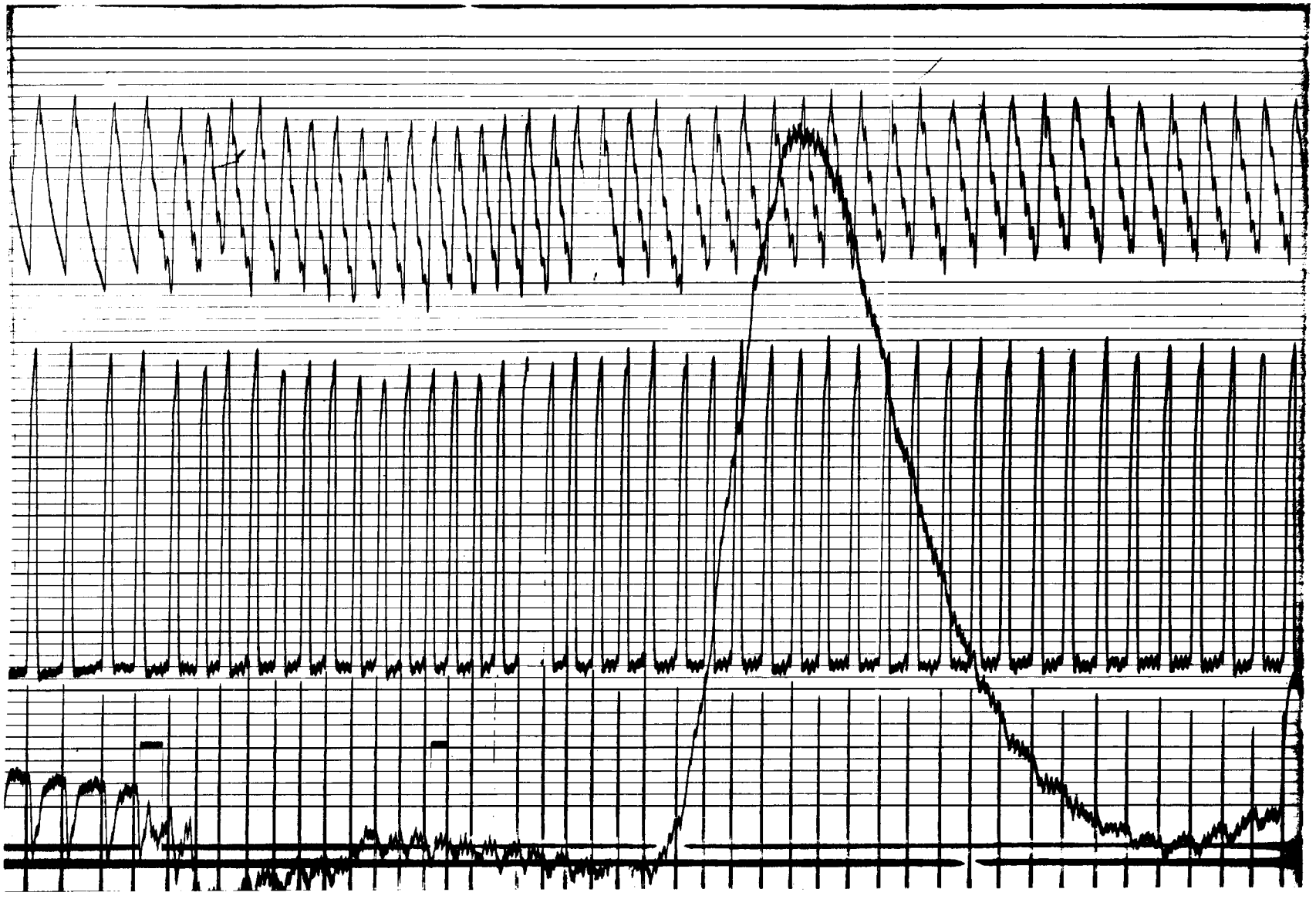


Fig. 1(b) - From top: Thoracic aortic pressure, LVP, $(dp/dt)_{max}$ of LVP. Dye curve superimposed. Apnea and vibration at 7 cps and 1/2" td after propranolol

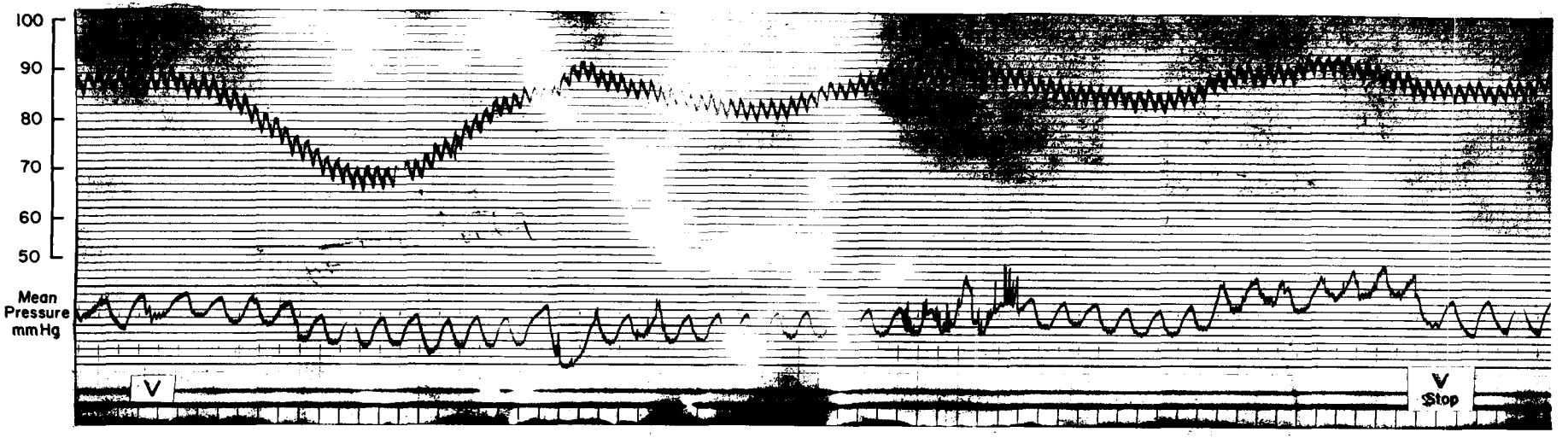


Fig. 2 - Vibration 7 cps, 1/2" td after phenoxybenzamine and propranolol. Mean blood pressure above; respiratory excursions below. Time marks at bottom in seconds. V = vibration

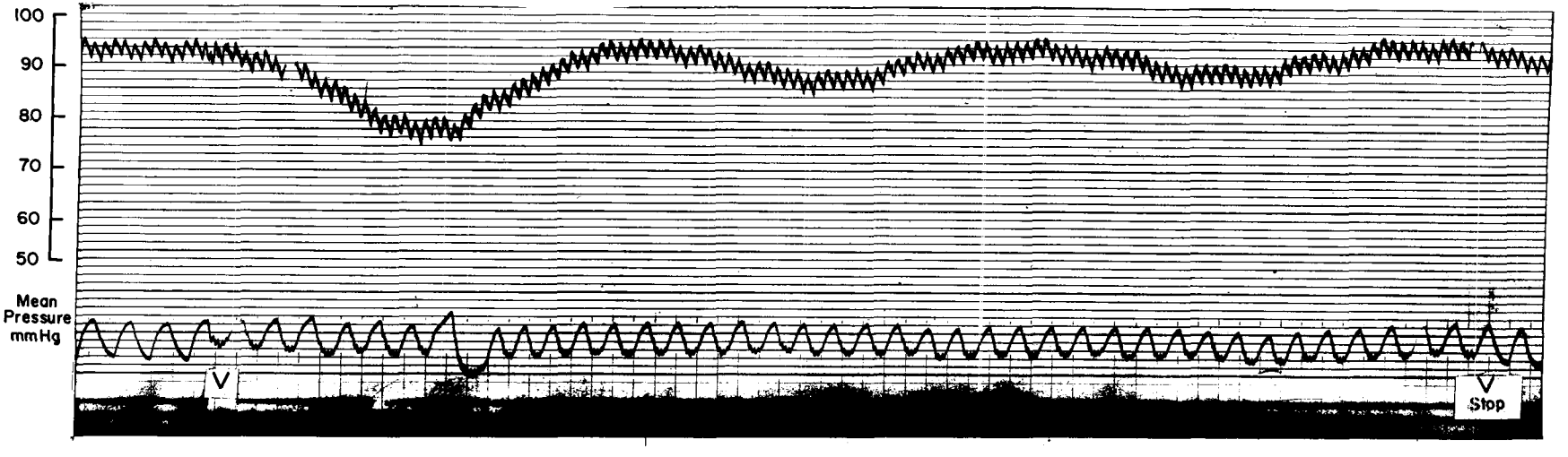


Fig. 3 - Vibration 7 cps, 1/2" td after phenoxybenzamine, propranolol, and atropine. Mean blood pressure above; respiratory excursions below. Time marks at bottom in seconds. V = vibration

findings are confirmed one must conclude that the effects of vibration on the peripheral vascular resistance result from

(a) a direct effect on smooth muscle components of arterioles comprising the high-resistance circuit,

(b) an indirect effect on smooth muscle as a sequel to local metabolic changes, or

(c) a release of a histamine or a histamine-like substance by mast cells.

SECTION II

BODY-VIBRATION AND THE ELECTROCARDIOGRAM

--The effects of electrode design, skin preparation, and electrode placement in reducing electrical noise in electrocardiograph signals obtained from human subjects during vibration

INTRODUCTION

ECG tracings obtained from experimental human subjects while they are being vibrated contain more or less electrical noise, depending on the vibration intensity and a variety of other factors. Since the noise is often sufficient to make research clinical interpretation of the traces difficult or impossible, it is desirable to determine the factors contributing the noise and to find ways to reduce it. This is the object of this study.

EXPERIMENTAL PROCEDURE

In a series of experiments, ECG electrodes of conventional and varied design were applied to the skin of human experimental subjects using various skin preparation and electrode application techniques. ECGs were recorded with subjects standing and seated, and at rest and while being vibrated at various vibration intensities.

The Frank[2] orthogonal lead system which was generally used requires leads to be placed on the body at locations illustrated in Fig. 4. ECG signals from the three orthogonal leads were recorded on magnetic tape and on photosensitive paper. Some exploratory recordings were made using standard leads and conventional ECG recording equipment. Recordings were evaluated on the basis of noise content and general fidelity as compared with control (no vibration) recordings.

Preliminary tests, specific reported observations of others,[3,4,5] and a general review of the pertinent literature, led to the following tentative conclusions:

(A) When ECGs of vibrating human subjects are being recorded there are at least four signals that can contribute to the signal seen at the ECG amplifier input. These signals are

(1) the desired noise-free ECG signal;

(2) undesired electrical noise, generally mostly random in nature, which is generated or picked

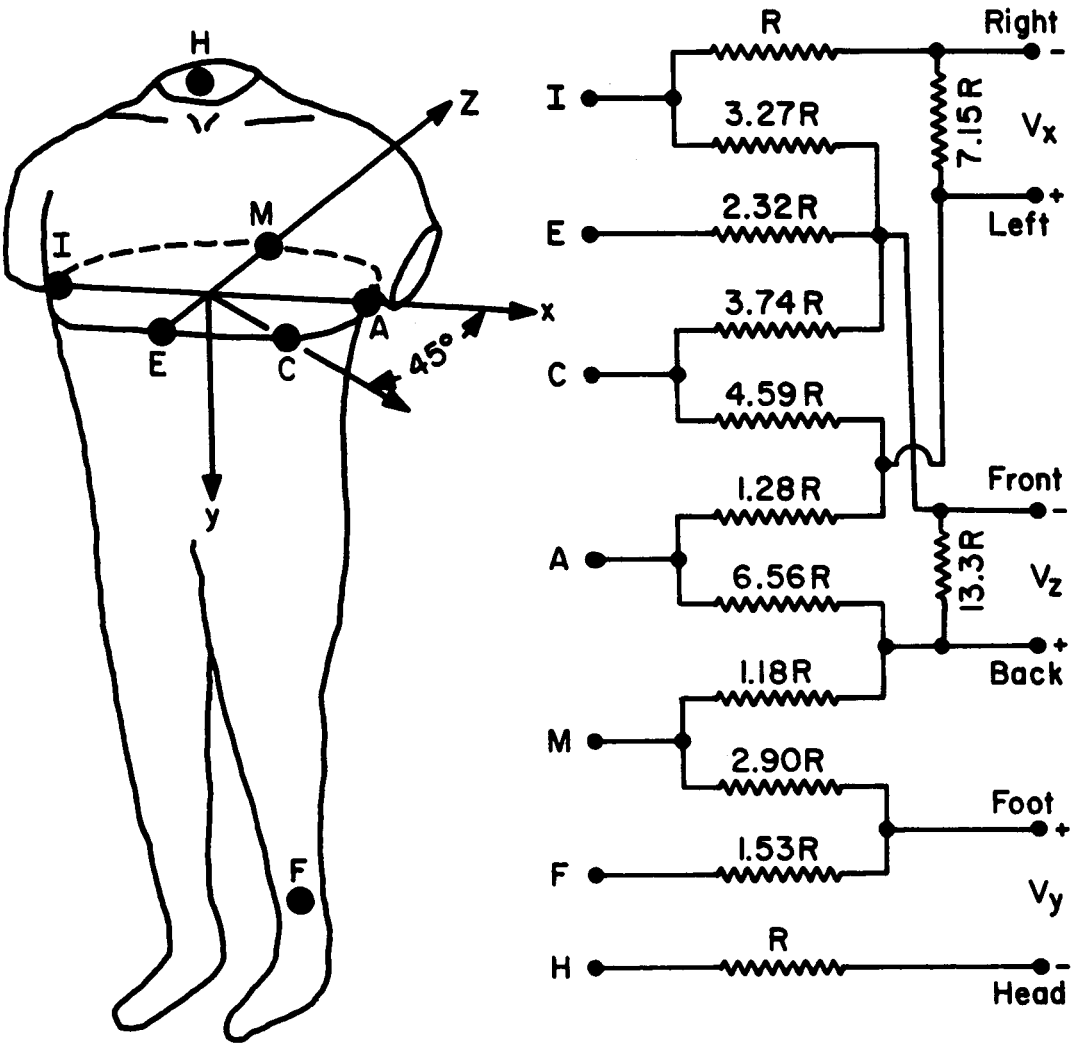


Fig. 4 - Frank system of electrode placement and compensating electrical network

up in the electrode system (a) at the electrode paste-skin interface, (b) at the electrode paste-electrode interface, (c) at the electrode paste-electrode housing interface, (d) at the electrode lead wire junction, or (e) in the electrode leads;

(3) undesired electrical noise from muscle; and

(4) undesired electrical noise of unknown origin, which probably emanates from within the body, which seems related to the vibration, and which takes the general shape of the vibration pattern.

(B) The undesired electrode system noise referred to in A(2) above is more or less sensitive to:

(1) electrode design, fabrication, and maintenance;

(2) security of electrode attachment;

(3) skin preparation;

(4) electrode paste formulation and physical characteristics;

(5) electrode lead static electrical characteristics; and

(6) electrode lead magnetic pickup.

(C) The undesired muscle noise referred to in A(3) above varies with vibration character and intensity; and electrode location on the body in relation to muscle mass and tone, muscle voluntary activity, the muscle groups used to defend against vibration, and the muscles affected by vibration.

(D) The undesired electrical noise of unknown origin referred to in A(4) above varies with electrode location, vibration characteristics, and vibration intensity. (Further study of this noise might be of physiological interest.)

TESTING AND DEVELOPMENT PROGRAM

Using the above tentative conclusions as a guide, a program of evaluation by testing and development of speciifc equipment and procedures was initiated.

A. Electrode Evaluation

The following electrodes were evaluated as described using conventional plate electrodes as references (see Fig. 5E):

(1) NASA electrodes as described by Day and Lippitt[3] (Fig. 5A, D),

(2) Beckman #350069 biopotential skin electrode (Fig. 5B),

(3) Avionics Metretel disc type electrode (Fig. 5C), and

(4) Conductive Paint electrode as described by Roman[6] (not shown).

The Conductive Paint electrode, which possesses the attractive advantage of low mass, did not perform well for us under vibration conditions, probably because of noise generated at the lead-paint junction. Further testing of this electrode is contemplated.

The Avionics electrode is a vast improvement over the conventional electrode but is noisier than the two electrodes to be discussed below. The design (small flange) does not permit firm attachment to the skin without immobilizing a large skin area.

The Beckman and NASA electrodes are considered together since they are of similar design and both are superior with regard to low noise generation and pickup. The combination of wide flanges and the use of double-adhesive tape facilitates firm attachment of the electrodes to the skin. Both electrodes have relatively low mass and both provide protection of the electrode lead-electrode junction. When in prime condition both electrodes can give excellent ECG traces, even under severe vibration conditions, if lead combinations are chosen which are relatively free of muscle noise and if the skin at the electrode site is properly prepared.

In our tests the NASA electrode performance deteriorated faster after repeated use than the Beckman electrode. However, the NASA electrode can be easily reconditioned (reanodized). Both electrodes can be pre-tested for noise using the method described by Day and Lippitt.[3] In our opinion the NASA electrode is easier to clean; however, cleaning is not a serious problem with either electrode.

B. Skin Preparation

The following methods of skin preparation were tested:

(1) No preparation,

(2) Scrubbing with alcohol,

(3) Scrubbing with acetone,

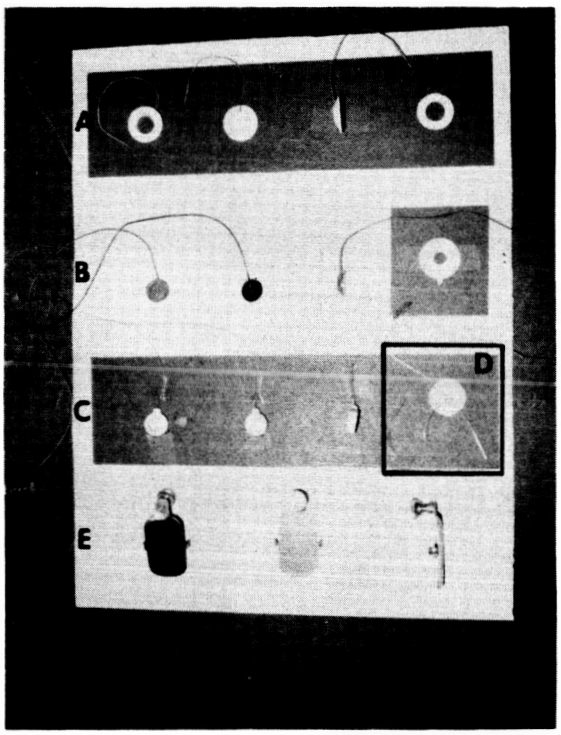


Fig. 5 - (A) NASA electrodes with adhesive collar
(B) Beckman #350069 biopotential skin electrodes with adhesive collar
(C) Avionics Metretel disc-type electrodes
(D) NASA electrode modified for use with saline solution as an electrolyte
(E) Cambridge conventional electrodes

(4) Application of silver nitrate,

(5) Pricking skin with needle,

(6) "Drilling,"[3] and

(7) Transparent tape stripping.

As expected, it was observed that during vibration low-level ECG noise is associated with low electrode-skin resistance. In order to obtain low electrode-skin resistance, it is necessary to prepare the skin electrode site by decornification of the skin to penetration of the epidermis.[7] Application of alcohol or acetone as the only skin preparation, which, of course, does not involve epidermis penetration, generally results in an electrode-skin resistance in excess of 10KΩ. ECGs obtained during vibration with electrode sites so prepared are noisy.

Electrode sites prepared by the application of a spot of saturated silver nitrate result in high electrode-skin resistance but the ECGs obtained during vibration are less noisy than would be expected to be associated with the high resistance.

Preparation of electrode sites by pricking the skin with a needle has been recommended for electrodes to be used on exercising subjects. Multiple needle pricks are required to be effective for ECG noise reduction during vibration. The effectiveness varies with the skin site being prepared and the person administering the needle pricks. Short of frank trauma, it is dufficult to pre-estimate the probable effectiveness of this skin preparation procedure.

The drilling method which uses a high-speed rotating dental burr for skin decornification requires a degree of skill on the part of the operator to obtain the desired epidermis penetration without excess trauma. The effectiveness is difficult to pre-estimate.

A method of skin decornification with inherent control over cornium removal was suggested to us by Dr. Ralph Carr (Associate Professor, Division of Dermatology, Department of Medicine, The Ohio State University). Layers of cornium are stripped off by repeated application and removal of the sticky side of transparent tape to the skin. As developed for electrode preparation, the procedure is given below.

A mask is prepared by cutting a hole one-quarter-inch in diameter in a piece of transparent tape approximately one inch wide and two inches long. The hole of the mask is placed at the electrode site and the mask stuck to the skin. A strip of transparent tape is placed on the mask and skin. This strip of tape is stripped off, a fresh piece of transparent tape put on and stripped off and this process repeated until the desired amount of decornification and epidermis penetration has been attained. Normally 10 to 15 strippings are required, depending on the nature of the skin at the selected location. More strippings are

required above the ankle and at the back of the neck than elsewhere. With experience it is possible to pre-estimate accurately from the appearance of the skin the amount of stripping required. The area is considered adequately prepared when the skin first appears moist and shiny patches appear.

The resistance (determined by a technique to be described) of a pair of electrodes prepared in this manner is often less than 600Ω. The subject will feel some discomfort when the decornification is carried to the appearance of a shiny patch. A red circular area will be prominent and persist on the skin for a few days, with or without slight scab formation. The above treatment gives ECG noise reduction adequate for extreme vibration intensity. Investigations limited to lower vibration intensities require relatively less decornification with correspondingly less severe preparation.

Measurement of Skin Resistance

An unconventional method of measuring electrode pair resistance was tried and found to be convenient. The method is based on the conventional method of determining internal resistance of a practical emf source. First the voltage output is measured with a very high impedance voltmeter. A variable shunt resistance is then applied across the voltage source and adjusted until the resistance is one-half the original value. The shunt resistance is then equal to the internal resistance. In ECG applications the heart is the emf source and the ECG is the voltmeter. Shunt resistance (decade box) is adjusted until the ECG-recorded R wave is one-half its amplitude with no shunt resistance connected. The shunt resistance is then equal to the total resistance between electrodes, including electrode resistance. The method is illustrated in Fig. 6. Since using the method we have found that it is also in use in Great Britain at the Medical Research Council.

C. Electrode Placement

Using the Frank orthogonal lead system, better tracings are generally obtained from the X and Z axis than are obtained from the Y axis.

Generally X-axis electrodes which are placed around the chest at approximately the fifth intercostal space are relatively free of noise during vibration.

Skin movement per se does not generally generate excessive noise. Electrodes placed over fleshy parts of the body are usually less noisy than nearby electrodes over muscle or "tight" skin. Tracings recorded from a 267-pound, 18-year-old male student contained little noise although the electrodes were undergoing remarkable excursions at table frequencies near body resonance (see Fig. 7).

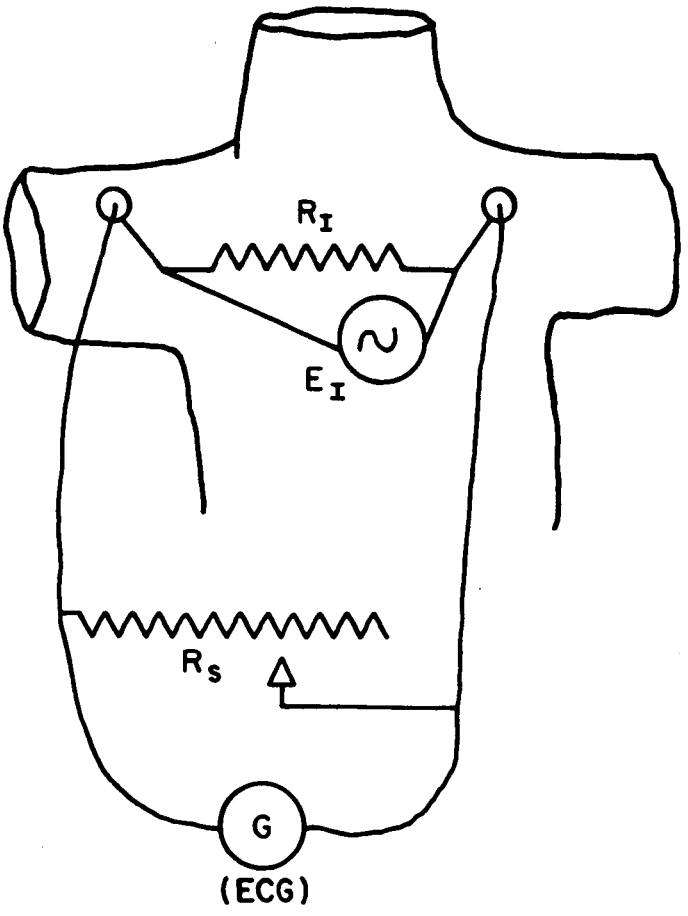


Fig. 6 - Schematic diagram for ECG electrode-skin resistance determination

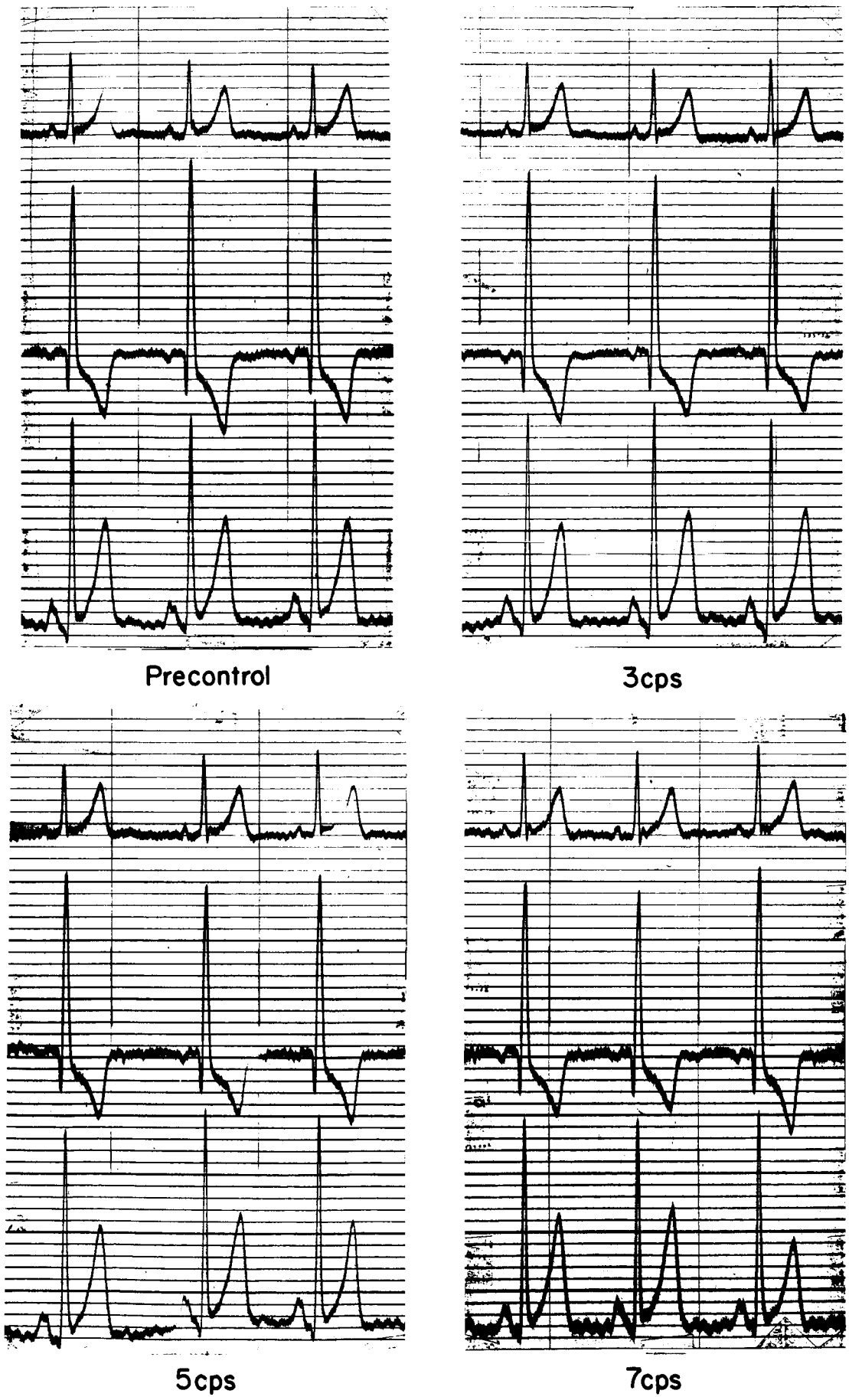
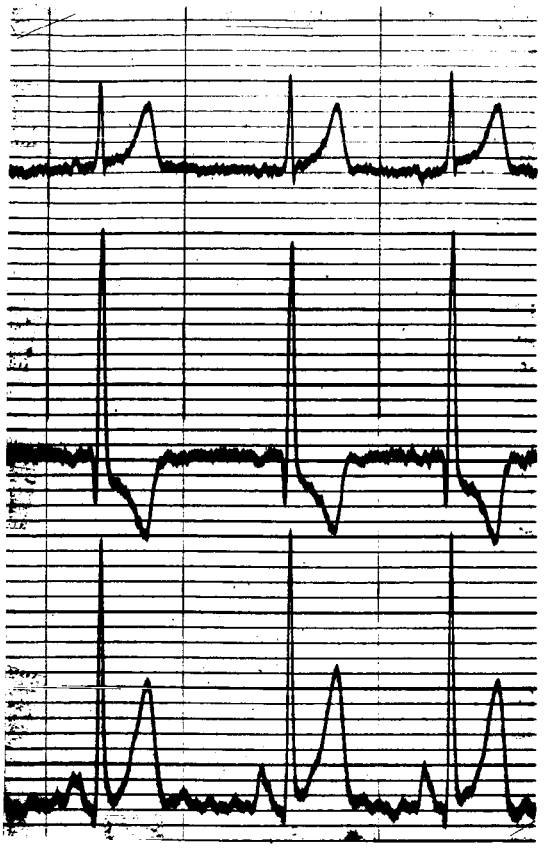
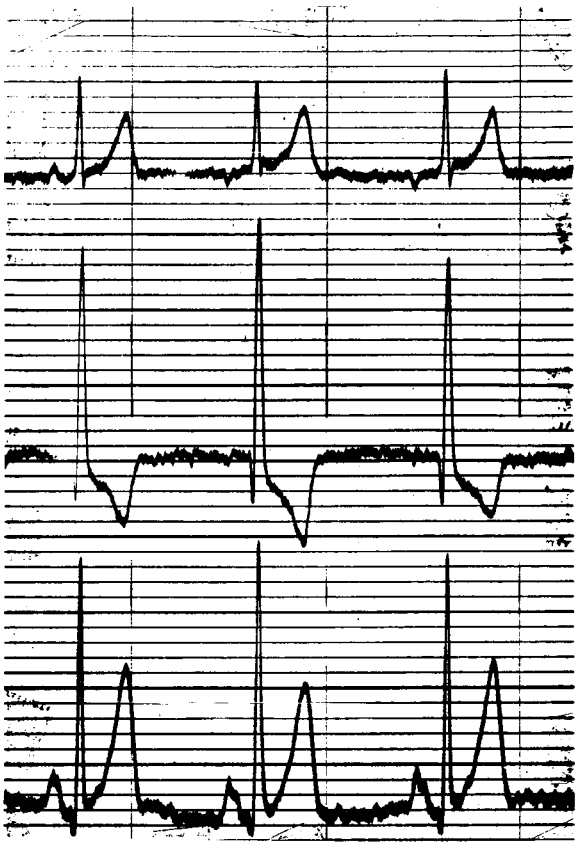


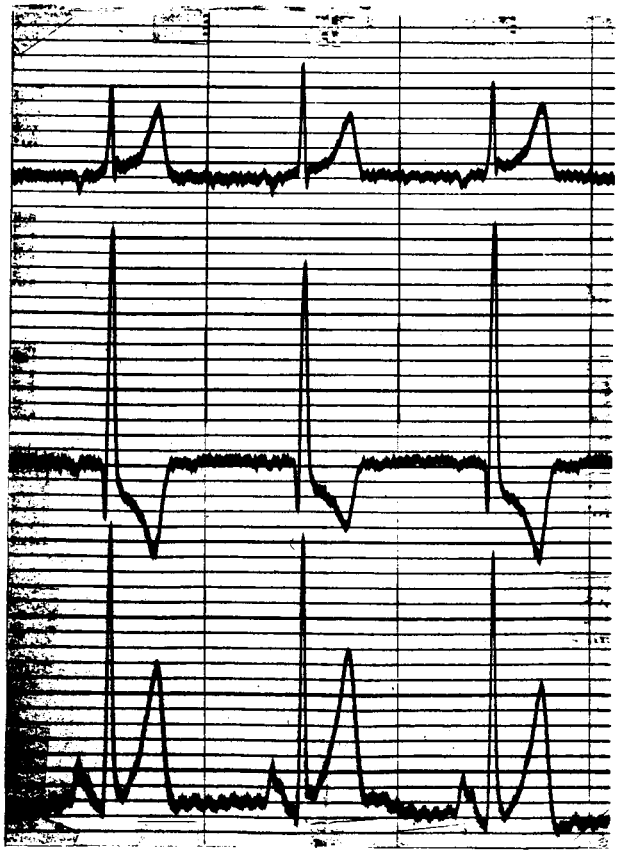
Fig. 7 - Traces from a sitting subject using the Frank lead system to obtain simultaneous recordings of all three axes



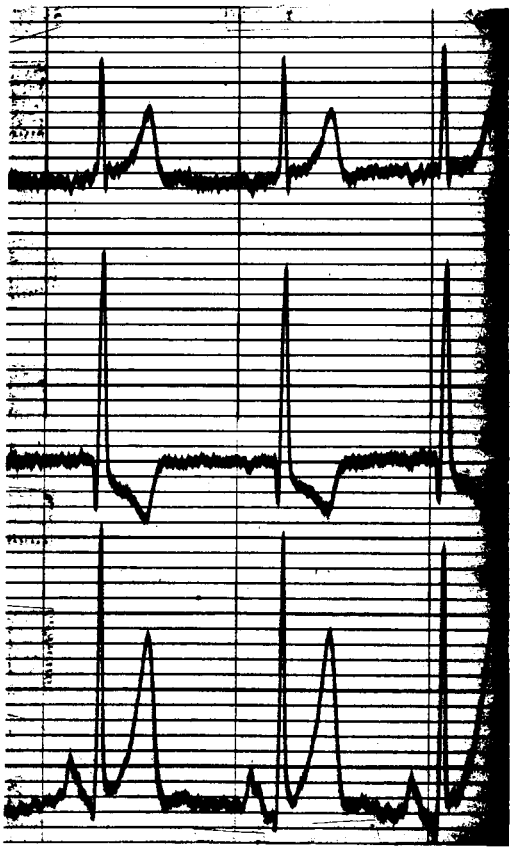
9cps



12cps



15cps



Postcontrol

Fig. 7 - (Continued)

Electrode Lead Wires

Microdot shielded lead wires especially designed to minimize noise generation during wire movement were used for all electrode leads. No special precaution was taken to shield or protect against electrical pickup caused by wire movement in the Earth or local magnetic fields.

Electrode Paste

Generally the electrode paste recommended by the electrode supplier was used although there was some interchange. Two NASA electrodes were modified (see Fig. 5D) so that they could be filled with liquid. The electrodes were filled with various concentrations of saline and the resistance measured. Figure 8 shows the resistance plotted against saline concentration. The lower resistance agrees quite well with the concentration of saline in NASA Jelly; i.e., 1ON NaCl.

SUMMARY

By using the NASA electrodes described[3]; preparing the skin electrode site using the transparent tape technique; attaching the electrodes as recommended; using noise-supressing electrode wire; and, using all of the above with normal high-quality electrocardiograph equipment, ECGs recorded from human subjects being vibrated can be expected to contain a minimum of electrical noise usually associated with ECGs recorded during vibration.

DISCUSSION

ECGs for monitoring so far obtained, using the above equipment and techniques, have been clinically acceptable without further treatment for research subjects being vibrated at intensities beyond short-term "tolerance" levels (severe vibration). Representative tracings are shown in Fig. 9-11. A systematic survey of more subjects is contemplated. Usually a low-amplitude background signal, which has the general characteristics of the vibration pattern, remains in the recorded trace. This is the signal of unknown origin referred to earlier. Its amplitude is frequency-dependent and since it is usually asynchronous with pulse rate, it appears to wander or flow in the ECG background. Thus it is generally possible, by studying a strip of recording, to discount this unwanted signal.

For critical studies, and especially when orthogonal leads are being studied, further treatment of the signals to remove additional noise may be desired. In such cases this may be accomplished by using the magnetic

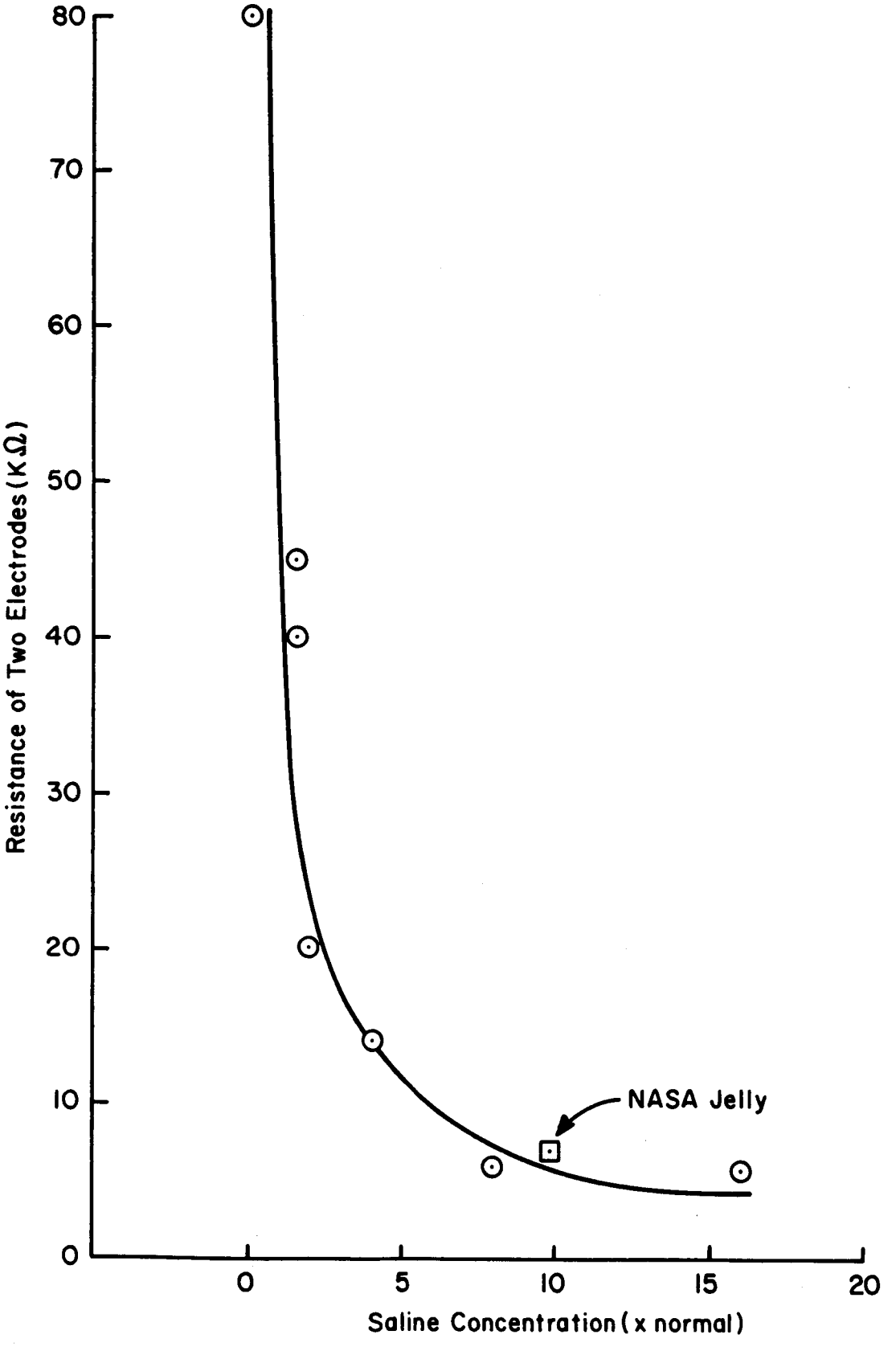


Fig. 8 - Electrode pair resistance using saline-filled electrodes; no skin preparation

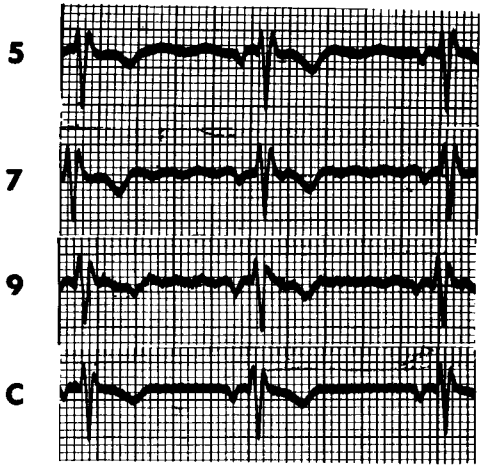


Fig. 9

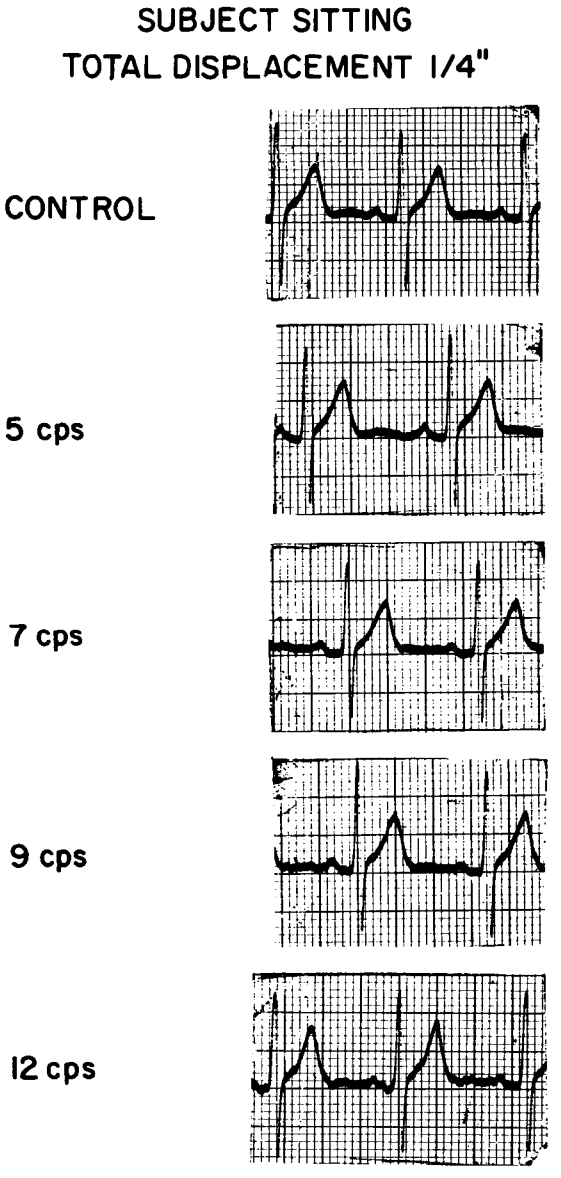


Fig. 10

ECG tracings obtained during vibration using NASA ECG electrodes and recommended skin preparation. Figures 9 and 10 show tracings from two chest leads in the Frank positions, M and I and C and I, respectively, (see also Fig. 4), on two different subjects vibrated in the sitting position at the frequencies indicated in the figure and at a total displacement of 1/4"

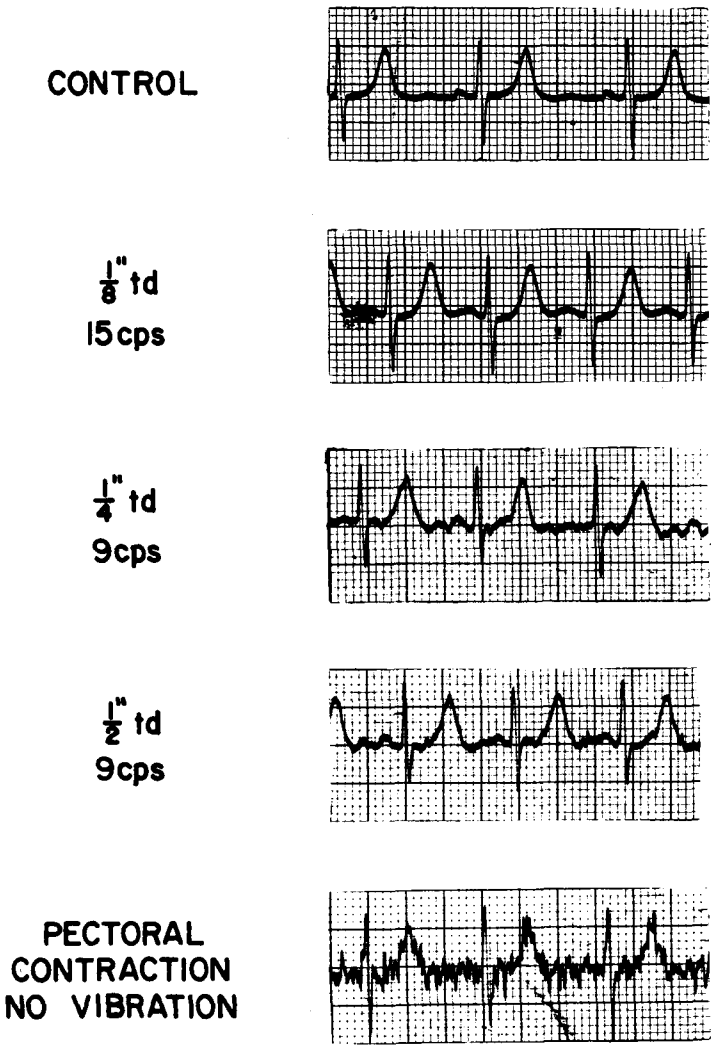


Fig. 11 - Traces obtained from a female subject with an electrode on each breast. Subject vibrated at frequencies and amplitudes shown

recording-computer signal averaging technique previously described.[1] Signals should be averaged during periods of uniform pulse rate to avoid excessive distortion of the pre (p) wave and late (t) wave segments of the trace. Distortion in the QRS complex is minimized since figuratively the averaging process is accomplished by first superimposing R waves then adding and averaging signals on either side of the R wave.

CONCLUSIONS AND STATUS

Subject to the results of the systematic survey of more subjects referred to above, it appears from the developments described here and in a previous report[1] that equipment and techniques necessary to obtain quality ECGs from humans while they are being vibrated are available. This should permit the ECG to be useful as a research tool in evaluating certain human cardiovascular physiological responses to vibration, and useful in evaluating certain stresses normally reflected in the ECG which are not necessarily of vibrational origin, but which must be measured in a vibration environment.

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