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UNIVERSITY OF CINCINNATI

May 31 19 51

I hereby recommend that the thesis prepared under my supervision by John Rutley Braunstein

entitled A DYNAMIC RECORD OF THE HEART BEAT

I- The Ballistocardiogram

II - The Vectorballistocardiogram

be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by:

O. A. Mills

Harold J. Kersten

H. A. Blankenhorn

FORM 668—G. S. & T. C.—500—5-48

A DYNAMIC RECORD OF THE HEART BEAT

A dissertation submitted to the
Graduate School of Arts and Sciences
of the University of Cincinnati
in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy
1951

by

John R. Braunstein

A. B. University of Cincinnati 1928
M. D. University of Cincinnati 1943

FOREWORD

This dissertation is offered in two parts. Part I consists of a monograph entitled "The Ballistocardiogram" which will be published by Charles C. Thomas in the series "American Lectures in Circulation" under the editorship of Irvine C. Page and A. C. Corcoran. Since no book however small has yet been published in this relatively new and little understood field, it attempts to present as simply as possible, and with a minimum of mathematics, a comprehensive picture of a physiological technique which offers promise not only in circulatory investigation, but also in clinical cardiology.

Our own laboratory is a newcomer in the field and most of the work cited is by others. Moreover we have attempted to move slowly and along fundamental lines. We have, at least, settled the controversy as to whether the ballistic table should be of high or low frequency in order to reproduce accurately the forces acting upon it. This is discussed in the appendix. We have also described the high frequency ballistocardiograph which moves in the frontal plane of the body and records simultaneously displacement at four points. This is briefly discussed.

Part II represents original work which is a logical outgrowth from investigations performed with the two dimensional instrument mentioned above. After this was built and,

after much difficulty installed in the basement of the Cincinnati General Hospital, it soon became apparent that the two displacements would be much more meaningful if they could be synthesized. How it was accomplished is described in this part entitled "The Vectorballistocardiogram".

ACKNOWLEDGMENTS

I wish to thank Dr. Johnson McGuire, who is responsible for introducing me to this field, and to thank both him and Dr. Harold J. Kersten for the opportunity to work in their respective laboratories during these past five years. Without their encouragement and assistance none of this work such as it is could have been accomplished. I am also indebted to Dr. M. A. Blankenhorn, Head of the Department of Medicine and Dr. Clarence J. Mills, Chairman of Graduate Studies in the Department of Medicine for their support and encouragement. Dr. Boris Podolsky has been most helpful with advice concerning the analysis of such a highly complex system as the ballistocardiograph has proved to be. Finally I must acknowledge the assistance of the late Dean Gowdy during the early days of this investigation.

PART I

THE BALLISTOCARDIOGRAM

PREFACE

This monograph represents a pair of lectures delivered at the University of Cincinnati in the Spring of 1951. No attempt has been made to cover the field of ballistocardiography in specific fashion, even though it is a small one. As a matter of fact, the time is not yet ripe for even a modest text; for if one were to be written today, it would be nearly useless by the time of publication. And yet it may not be without point to present, in more comprehensive fashion, a picture of this most challenging and rapid-moving field.

Cardiac Laboratory
The Cincinnati General Hospital
May 1951

John R. Braunstein

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LIST OF ILLUSTRATIONS

INTRODUCTION

It is something over ten years now since Isaac Starr coined the term ballistocardiogram, described a workable instrument to produce the record, and published his first major paper in the newly named field. In the interval, many cardiologists have been frankly skeptical of the tool, others have failed to grasp the physiological implications of the method, some hardy souls have tried to improve the technique; but only a few have been more than transiently attracted to a record whose fascination lies in the fact that in it is locked the secret of the dynamic action of the heart. Quite recently, however, the condition has begun to change. Many more papers are being published, both of a clinical and fundamental nature. Gradually the record is beginning to yield its secrets; and, although the field is now in a state of healthy flux, it may be worth while to take a look at its remote and recent ancestors, its present condition, and hazard a guess or two as to the direction it will take in the future.

HISTORY

What early man became first aware of his heart beat is lost in antiquity, whether or not he had yet woven a basket or baked a pot is unknown, and what biophysicist it was that secretly in the middle of the night applied the law of the conservation of momentum to his own heart action has not transpired, yet it remained for a modern Scot to make the first recording of the forces imparted by the heart to the body. In 1877 in a paper entitled "On Certain Molar Movements of the Human Body Produced by the Circulation of the Blood" J. W. Gordon describes a light bed suspended by ropes from the ceiling. He also describes an earlier record taken from a spring weighing machine which suggests that he made his invention while standing on one of these. A record taken by each of these techniques is shown in Figure 1. Nothing much seems to have come from Gordon's work, and a hiatus exists until 1905 when Yandell Henderson, who was unaware of Gordon's paper, suspended a plank from the ceiling by wires. Side motion of this plank was prevented, and the head to foot motion magnified by a series of levers and recorded on a smoked drum. His recording device is shown in Figure 2, and some of his early records in Figure 3. Henderson suggested that the amplitude of the record was related to the cardiac output. Unfortunately, however, his table, which had quite a long period, required cessation of breathing

Figure 1.

Illustrations from Gordon's Original Article. The left hand tracing is taken from a spring weighing machine. The right hand one from his constructed instrument. These early records illustrate the fundamental difference between the high and low frequency instrument.

Fig. 1.

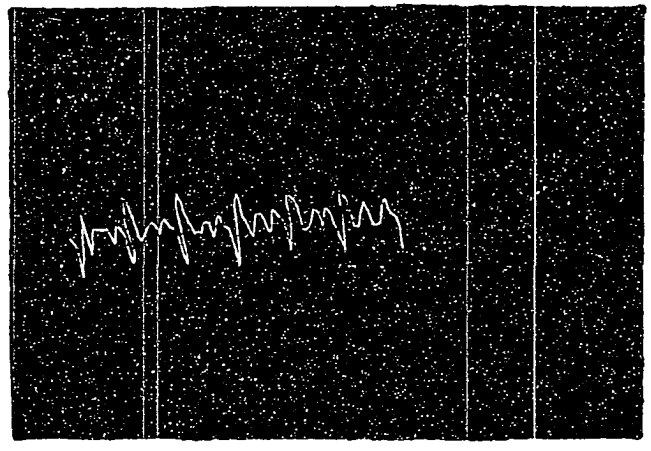
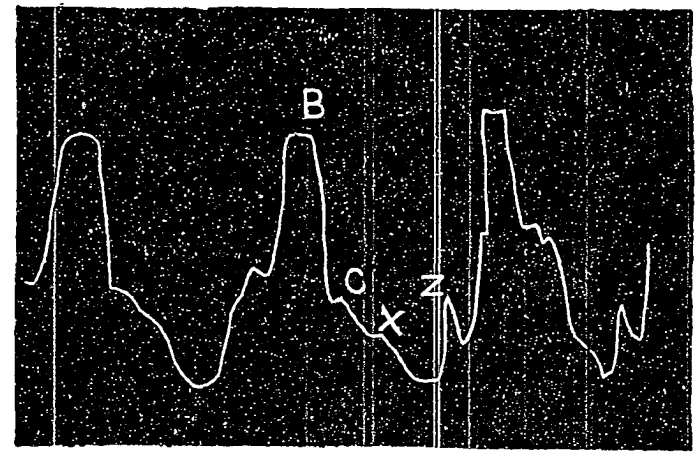


Fig. 2.



In Fig. 1 the downstroke which is immediately succeeded by a long upstroke is synchronous with the systole: the next downstroke is the second deflection referred to in the text. The upstrokes are to be regarded merely as indicating the instrumental tendency to restore equilibrium.

In Fig. 2 the letters bear the same significance as in Dr Galabin's figures. Vide infra.

Figure 2.

Henderson's recording device as illustrated in his original article. This is an excellent example of the crude type of the instrumentation with which so much important physiological work was done in the not too distant past.

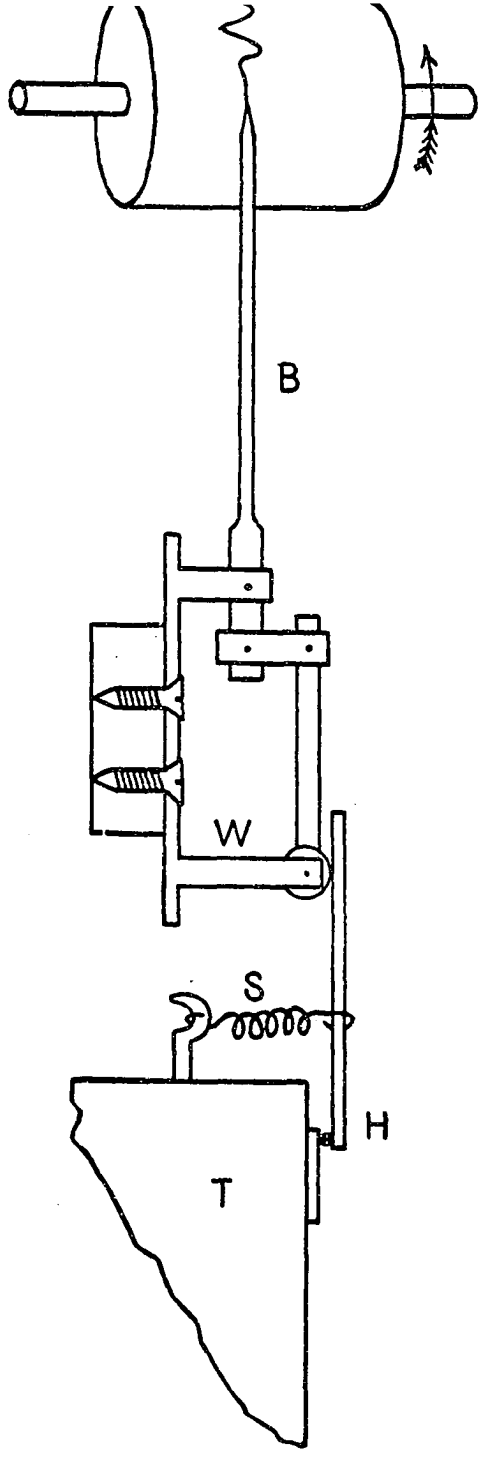
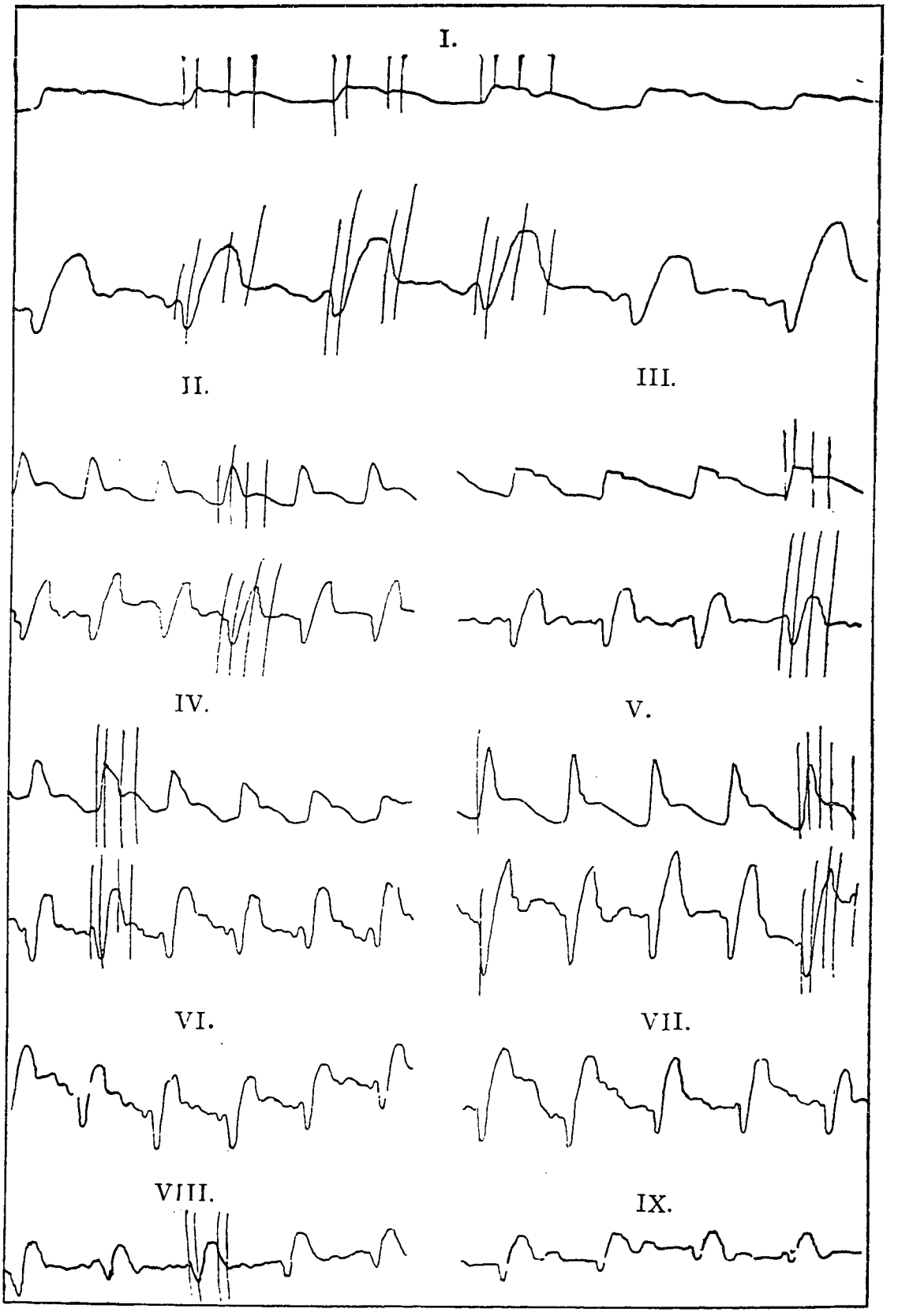


FIGURE 2.—In Figure 2 is shown the arrangement of the recording lever. Attached to one corner of the table *T* by the hinge *H* is a strip of stiff steel (15 by 1.2 by 0.2 cm.). By means of the spring *S* the strip of steel is held against the wheel *W*. This wheel is ground with the utmost precision to a diameter of 10 mm. Fastened to the wheel is an aluminum rod 10 cm. long which connects by means of a link with the lever *B*. The short arm of this lever, which is also of aluminum, is 3 cm. in length, the long arm to the writing point 15 cm. Thus every movement of the table is magnified 100 times with an error of probably less than 1 per cent. The advantages of the arrangement are that the connection between the table and lever is broken by simply loosening the spring, and that in any position of the table the lever is easily set to write upon any part of the smoked paper on the drum on which is recorded the recoil curve. Throughout these investigations a drum turning on a horizontal axis has been used, in order to avoid distortion of the recoil curve by the weight of the lever influencing the swing of the table.

Figure 3.

Some of Henderson's original "recoil curves". The upper of each of the paired curves is a pulse tracing. The lower is the "recoil curve". Vertical lines are time markings. Since the table had a long period, the records are not unlike those produced by Gordon's instrument (Figure 1, right hand tracing).

Circulation as Shown by a Recoil Curve.



with excellent and simultaneous muscular relaxation in order to obtain a record free of artefact, an athletic feat not easily achieved by the average subject.

In the thirty odd years which intervened between Henderson's paper and the early work of Isaac Starr numerous records were obtained in a variety of ways by different workers, but in no instance did any show the sustained interest, or singleness of purpose required to develop so complex a project. These are reviewed in Starr's early article. Douglas and his group (which included Henderson) used a plank supported on piles of cork during the Pike's Peak expedition to determine whether altitude affected cardiac output. Their observations may be noted in Figure 4 and the instrument employed in Figure 5. In the same year (1913) Thomas Satterthwaite of New York obtained a good record from a patient sitting on a spring weighing machine (Figure 6 and 7). Heald and Tucker (1922) devised a platform, on which the patient stood, which was suspended from the diaphragm of a drum. Change in the internal volume of the drum was recorded by changes in the current flowing through a hot wire placed in the inlet. This instrument is illustrated in Figure 8 and the results of an experiment performed on it in Figure 9. A few years later (1928), two German physicists, Angenheister and Lau, obtained records from a seismograph placed alongside a subject lying on a

Figure 4.

Records taken on the Pike's Peak expedition. The comments which are reproduced with the tracings are self-explanatory.

In the original account of this method a modification was described in which the plank, or recoil board, instead of being hung from wires, was supported upon rubber

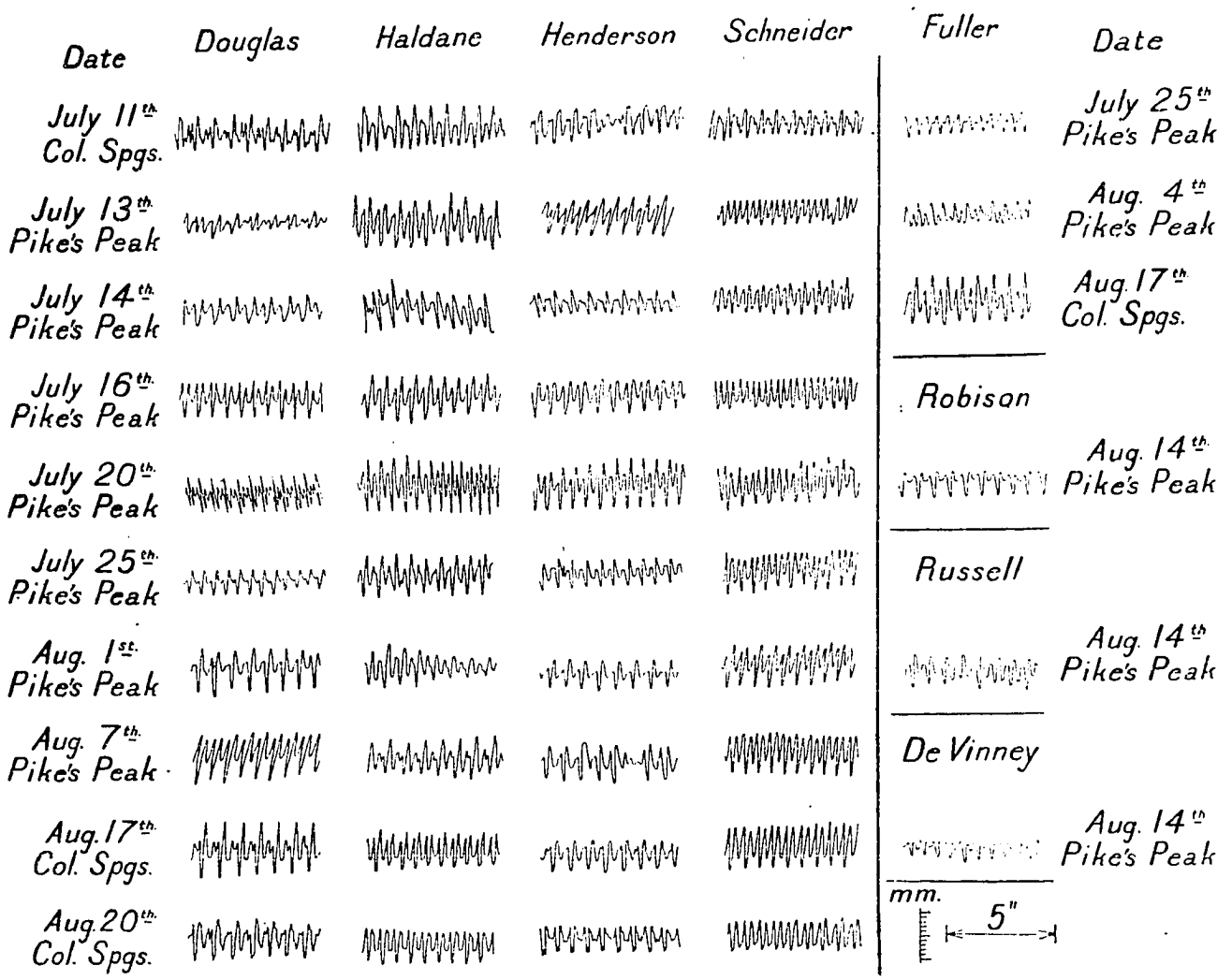


Fig. 16.

Recoil curves obtained with apparatus shown in fig. 17. The relative amplitude of the curve of any individual at any time is taken as an index of the systolic discharge of the heart. Note that the curves obtained in ourselves after acclimatisation to the altitude of the Peak were not sensibly different in size from the normals recorded in Colorado Springs. Nor are the curves of the regular summer inhabitants of the Peak, ROBISON, RUSSELL, and DEVINEY, notably different from those of men of corresponding physique at sea-level. Note also that in DOUGLAS on July 13, and in FULLER on July 25 and August 4, the condition of mountain sickness was accompanied by a marked diminution in the amplitude of the recoil curves. Somewhat the same phenomenon appears in the curve from HALDANE on August 1 after a carbonic oxide and low oxygen experiment. The occasional dropping of a heart beat in the records from HENDERSON was the result of tobacco, not altitude. In the right-hand lower corner are given the original scale of the height and duration of the curves.

Figure 5.

The instrument used on the Pike's Peak expedition complete with subject in vest and stiff collar.

Figure 6.

Thomas Satterthwaite of New York employed a standard doctor's spring scale popular at the time to which he attached a long, light writing arm as illustrated. The second pen is a pulse recorder and the bottom one a time marker.

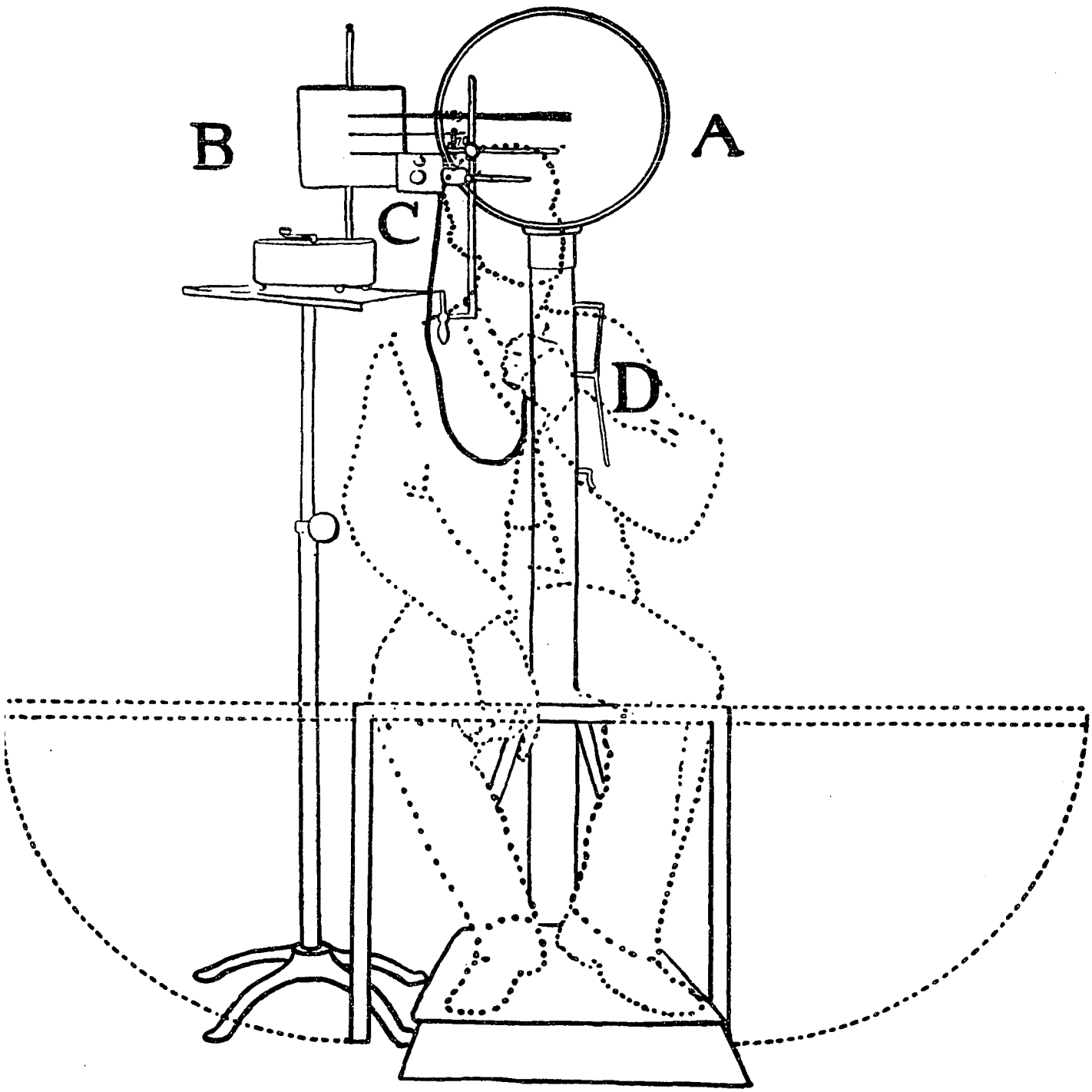


FIG. 41—Automatic lever and spring polygraphic machine or recorder.

Figure 7.

The record illustrated shows only what we now call the ballistocardiogram. Note that the head-foot convention is the reverse of that now usually employed.

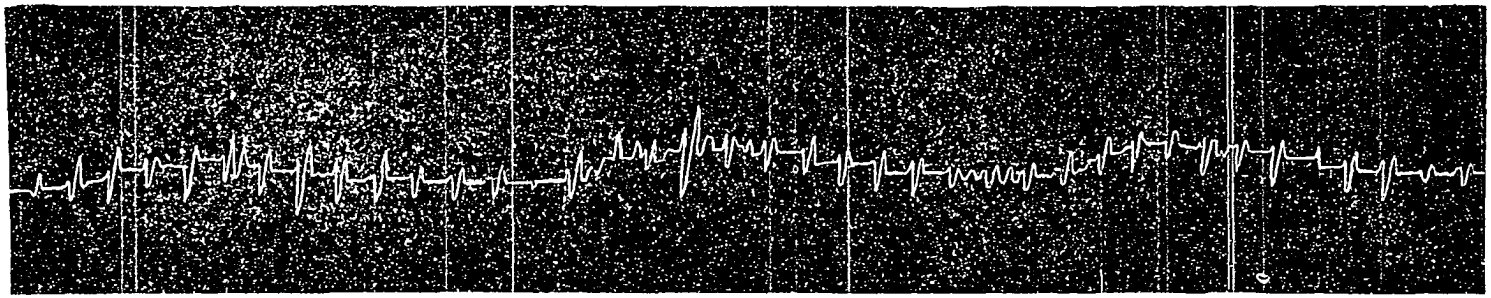


FIG. 42—Cardiovascular tracing, showing an irregular respiratory curve, in a pulse irregular as to force and rhythm.

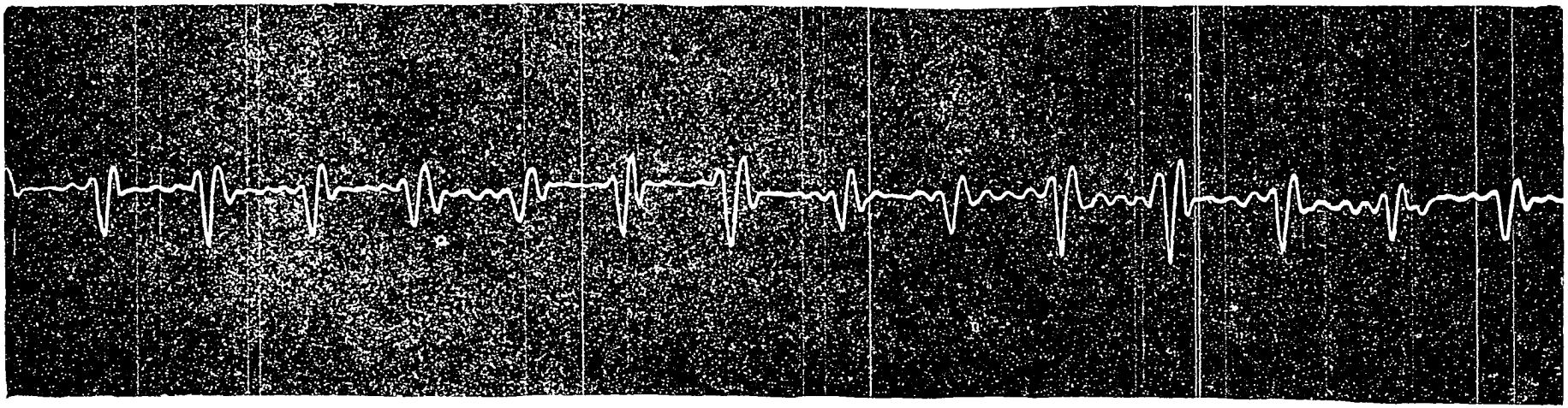


FIG. 43—Cardiovascular waves as taken by the automatic recorder. From the original, magnified three times.

Figure 8.

Heald and Tucker's Instrument.

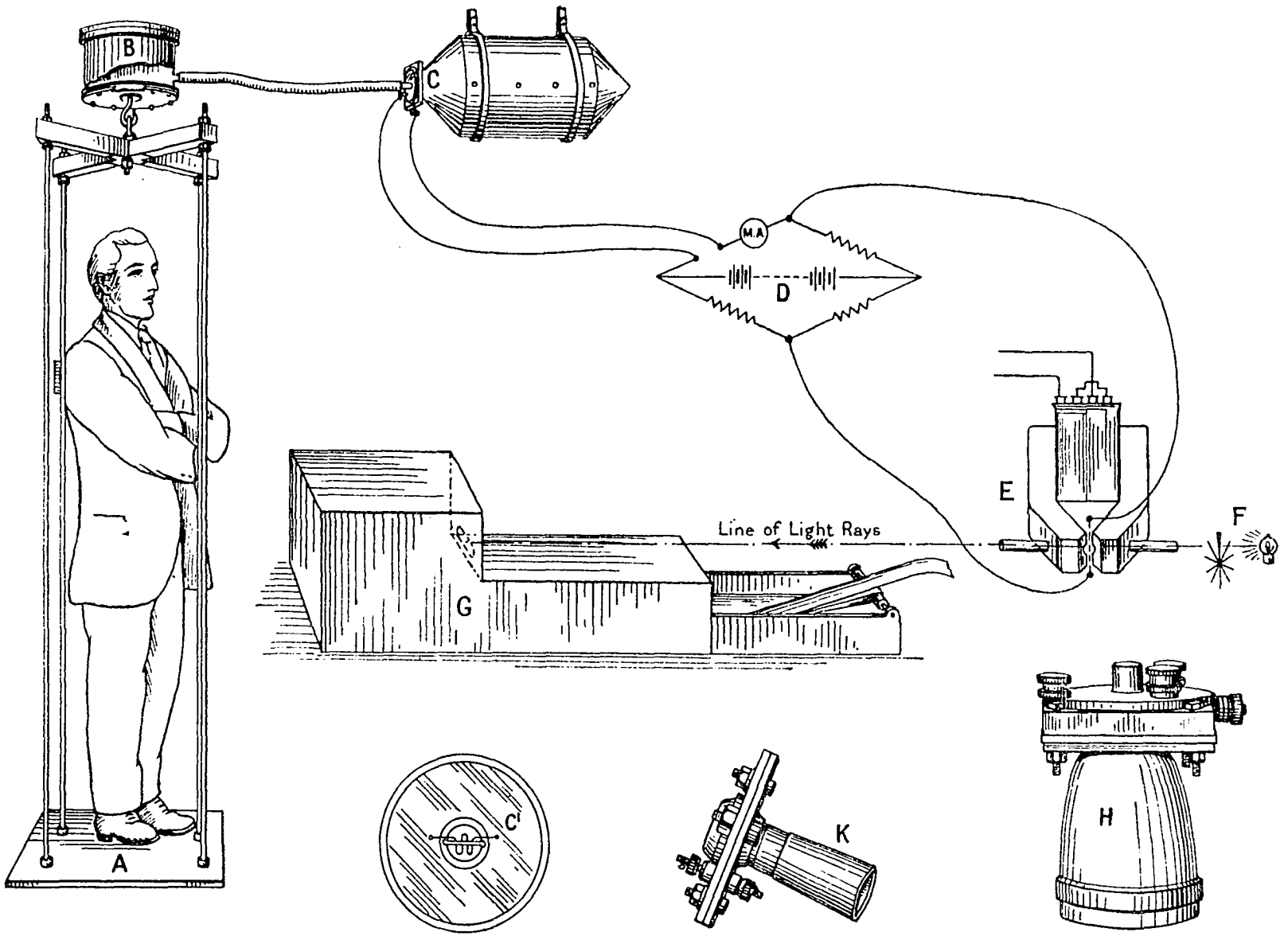


FIG. 1.

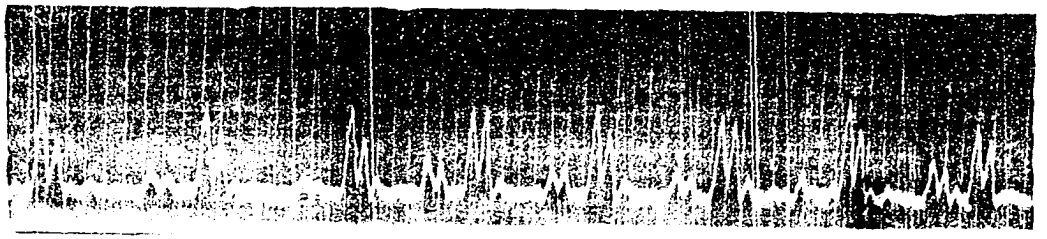
A, platform ; B, drum and diaphragm ; C, microphone and accessory cylinder ; C^1, microphone grid ; D, Wheatstone bridge circuit ; E, Einthoven galvanometer ; F, source of light and time wheel ; G, camera and automatic developer ; H, pulse microphone ; K, breathing microphone.

Figure 9.

Series of curves from one of Heald and Tucker's experiments. These look quite unlike curves previously illustrated since the hot wire was unable to tell which way the air was moving.

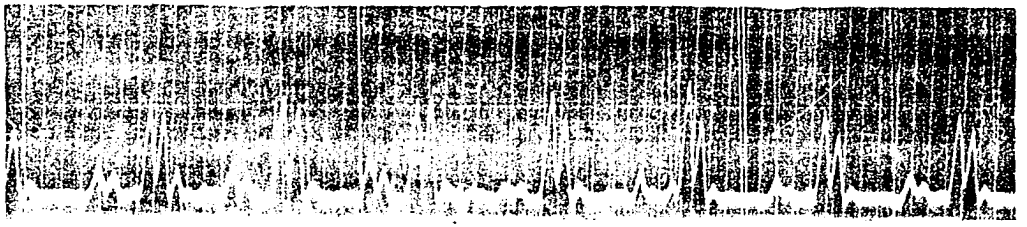
Fig. 11

(a) Normal Recoil Curve as general Control.

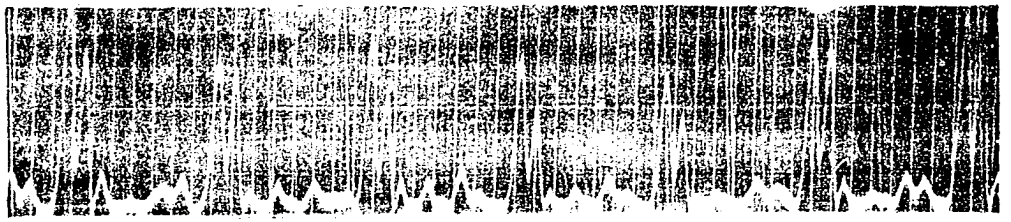


(b) 5 minutes after 1 ounce of Peppermint Water (to demonstrate presence of a psychological effect, if any). Showing no psychological effect produced.

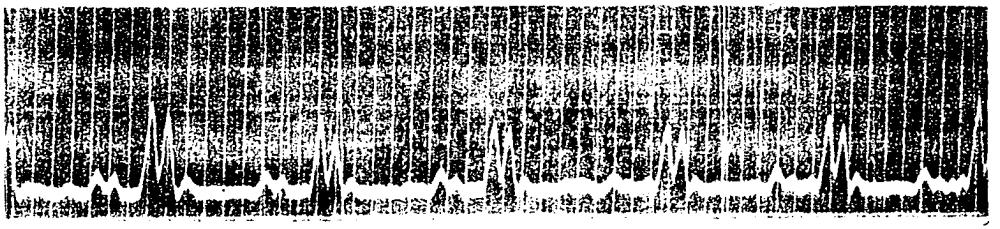
c) 5 minutes after 1 ounce of Peppermint Water, to which 15 drops of Liquor Adrenalin had been added.



(d) 5 minutes after 1 ounce of Peppermint Water, to which 1/150 grain of Nitroglycerin had been added. Showing great increase in second and third peaks.



(e) Control curve taken half-an-hour after (d), showing complete return to normal.



rigid table (Figures 10 and 11). In 1933 Abramson, a Swedish physiologist, built a chair of aluminum alloy suspended from springs imbedded in a cast steel base on a concrete foundation (Figure 12). This is said to have a natural frequency of 75 cycles per second when loaded with 70 kilograms of mass, an indication of the quality of the engineering employed in its construction. A record is illustrated at both slow and fast paper speeds in Figure 13. Abramson, however, soon became ill and his project was abandoned in spite of its auspicious beginnings.

In 1939, Starr published the now classic paper in which he described a simple and workable high frequency instrument, investigated the damping of the human body, and set up empirical equations for calculating the stroke volume and minute output of the heart. In the years which have followed, and in spite of World War II, he has continued to develop the field, which for all practical purposes he founded; and has made numerous contributions to ballistic theory, instrumental design, and the clinical application of the technique. During the war, Nickerson developed the so-called low frequency, critically damped ballistocardiograph. He and his followers were at first primarily interested in output studies and the theoretical implications of the method; but of late, papers of a clinical nature have begun to appear. Since the war, Dock,

Figure 10.

Method used by Angenheister and Lau. The table is supported on felt pads.

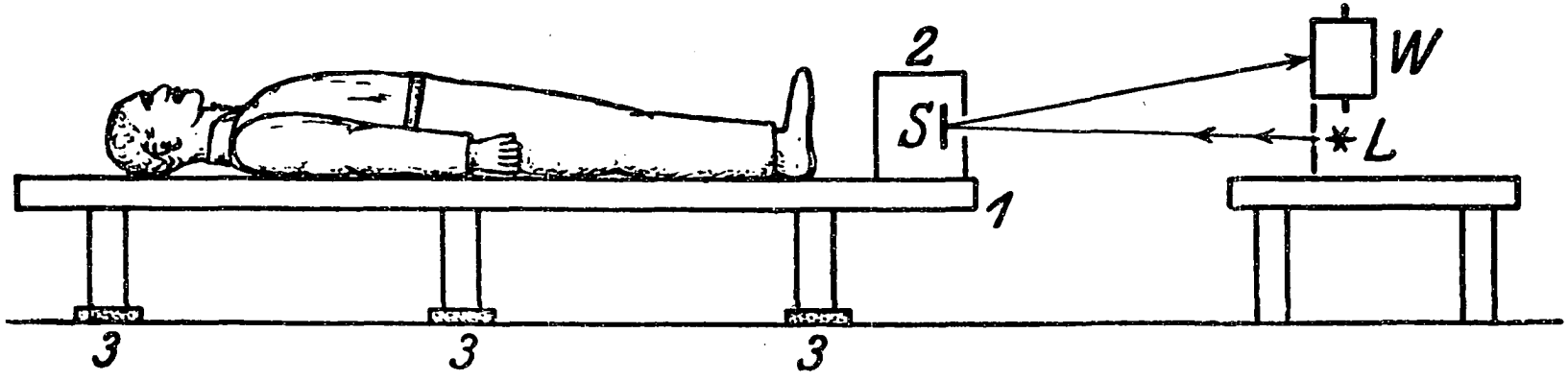


Fig. 6. Versuchsanordnung der seismographischen Aufnahme der Herztätigkeit. *1* Tisch; *3* Filzunterlage; *2* Seismograph; *S* Spiegel; *L* Lampe; *W* Registrierwalze.

Figure 11.

Records taken by Angenheister and Lau. In spite of the comparative excellence of these records, note the high frequency artefact probably due to building tremors.

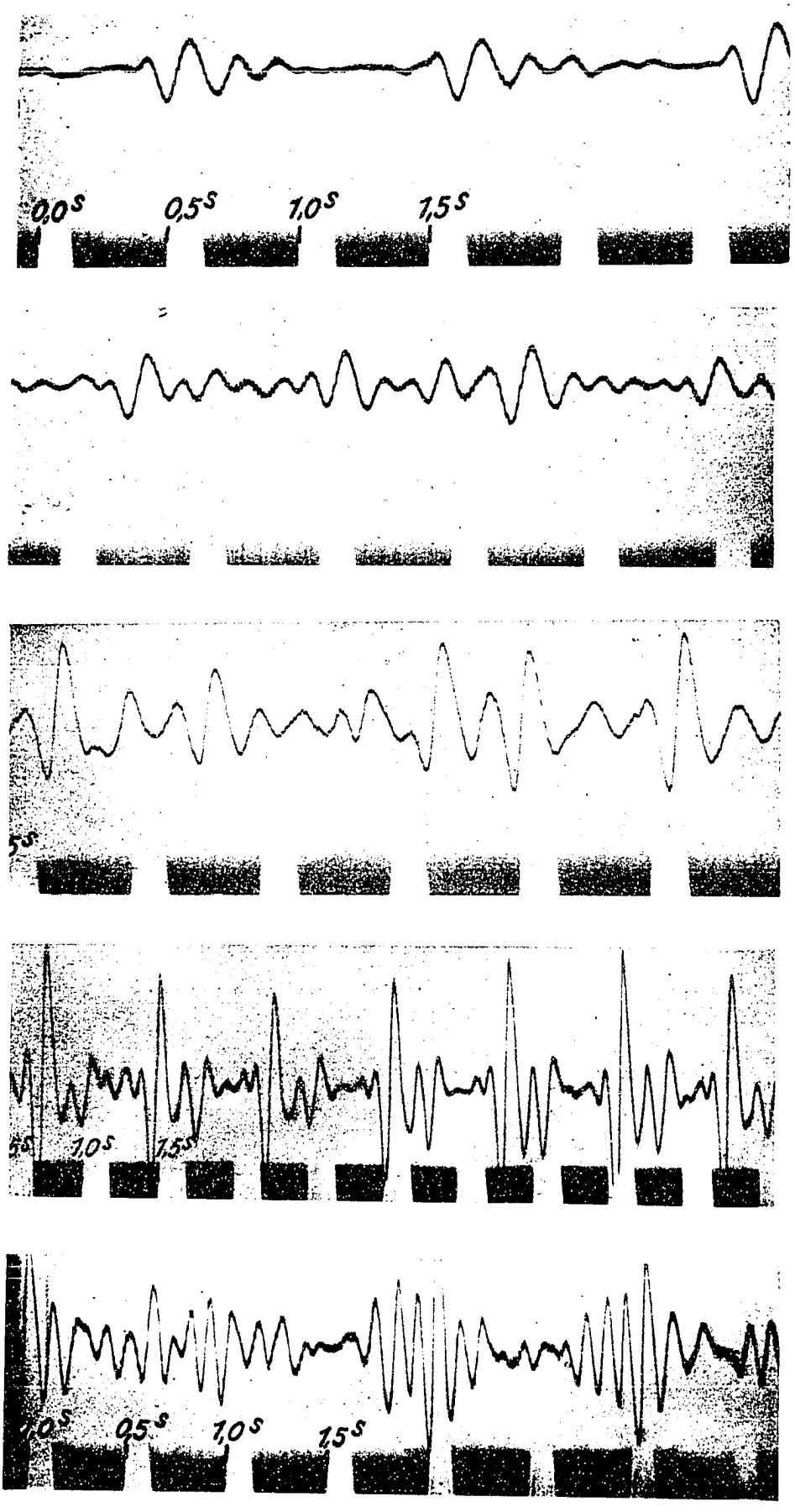


Figure 12.

Abramson's instrument together with a natural frequency curve obtained for it.

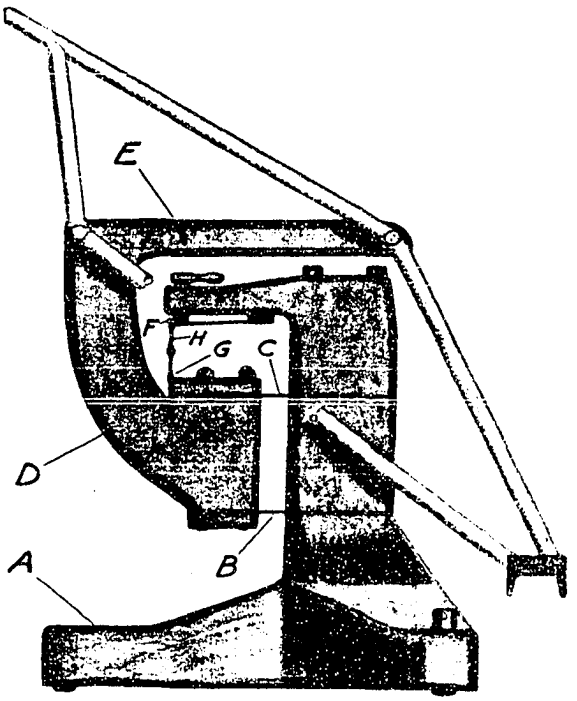


Fig. 6.
Schema des Kardiodynamographen.

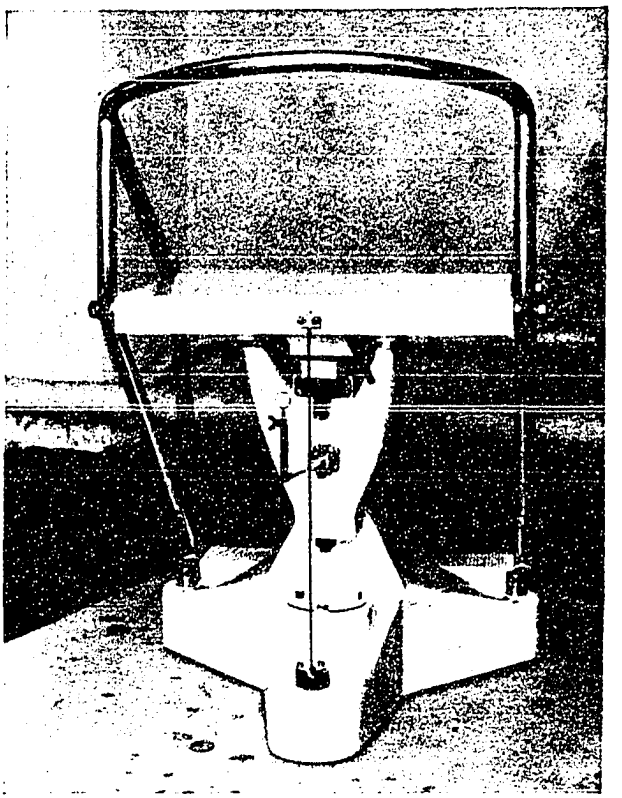


Fig. 7.
Der Kardiodynamograph von hinten.

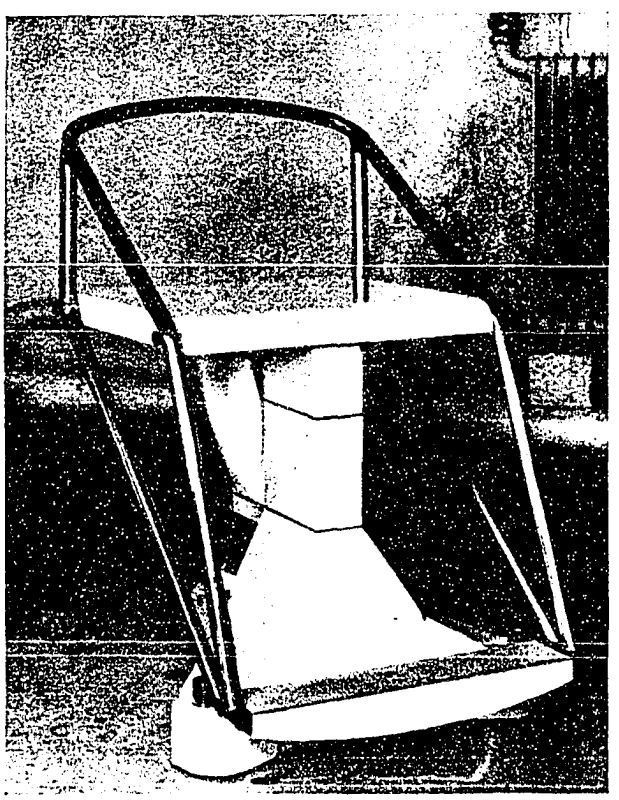


Fig. 8.
Der Kardiodynamograph von vorn.

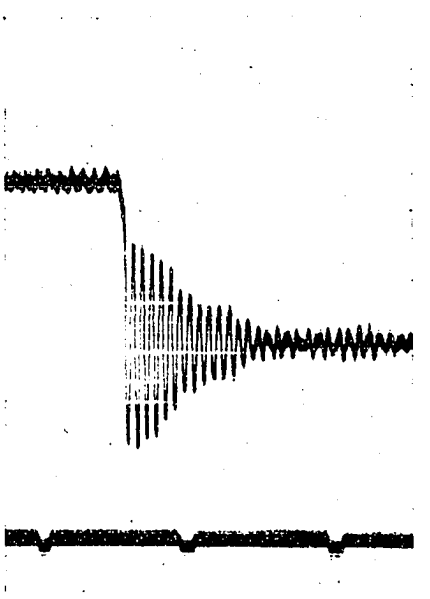


Fig. 9.
Eigenschwingungskurve des Kardiodynamographen. Zeit in $^1/_5$ Sek.

Figure 13.

A record from Abramson's machine at slow and fast paper speeds. Note that even here is some high frequency artefact in spite of a concrete foundation.

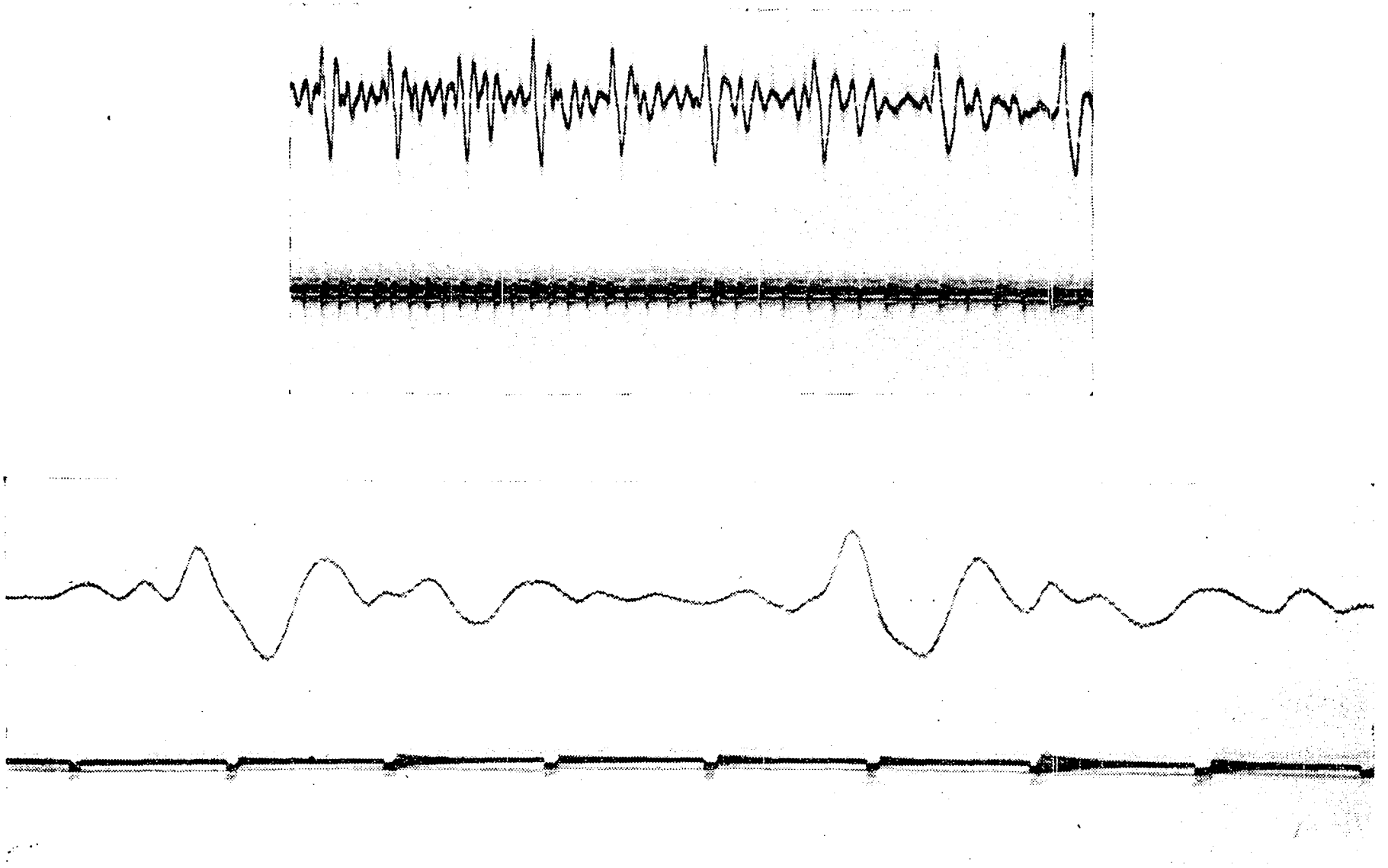


Fig. 14.

Ruhekurve mit normaler und mit größerer Geschwindigkeit des lichtempfindlichen Papiers aufgenommen.

realizing that the ballistocardiogram contained valuable clinical information, attempted to find a simple way of recording it. These three instruments will be considered in the next chapter.

Anyone, however, who wishes to evaluate critically these or other instruments which may be offered in the future may do well perhaps to stop at this point and read the appendix, (where a few simple principles of vibrating systems are considered) before proceeding.

MODERN INSTRUMENTS

When Starr built his now historic table, like Yandell Henderson, he suspended it by long wires from the ceiling. For his restoring force he used a piece of hardened tool steel "mounted on a rigid welded steel structure of pipe and channel, screwed to the floor and braced against the side wall". He prevented lateral motion with two struts attached to the wall through a flexible joint. Figure 14, taken from his original article, illustrates the construction. The natural frequency (f_n) of this table is 10.5 sec. when loaded with 150 lbs. of iron*. In the design of this instrument, Starr kept the bar responsible for the restoring force separate from the supports, a matter of some theoretical importance, since the supporting structure under the weight of the table and subject will undergo a small deformation. This consideration, however, probably introduces a negligible error, and has been ignored by most subsequent designers of this type. Figure 15 illustrates a commercial model now in production. This has extension feet, and can be moved from room to room. The loaded frequency of the instrument is advertised as above 14 c.p.s. Neither of these instruments has any damping**, but depends upon that provided by the subject.

*For definition of natural frequency see page 61.

**For definition of damping see page 61.

Figure 14.

Design for Doctor Starr's original table.

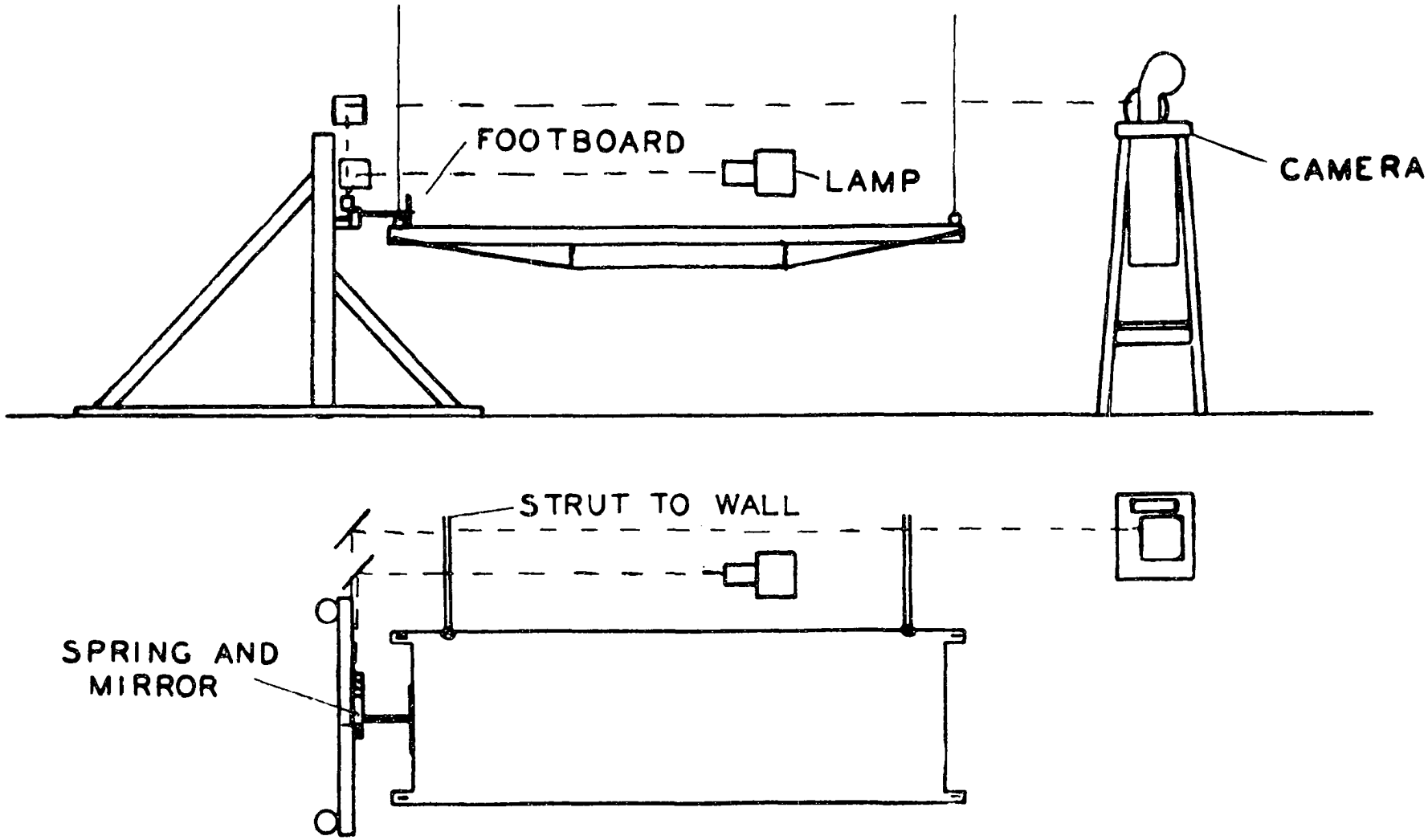
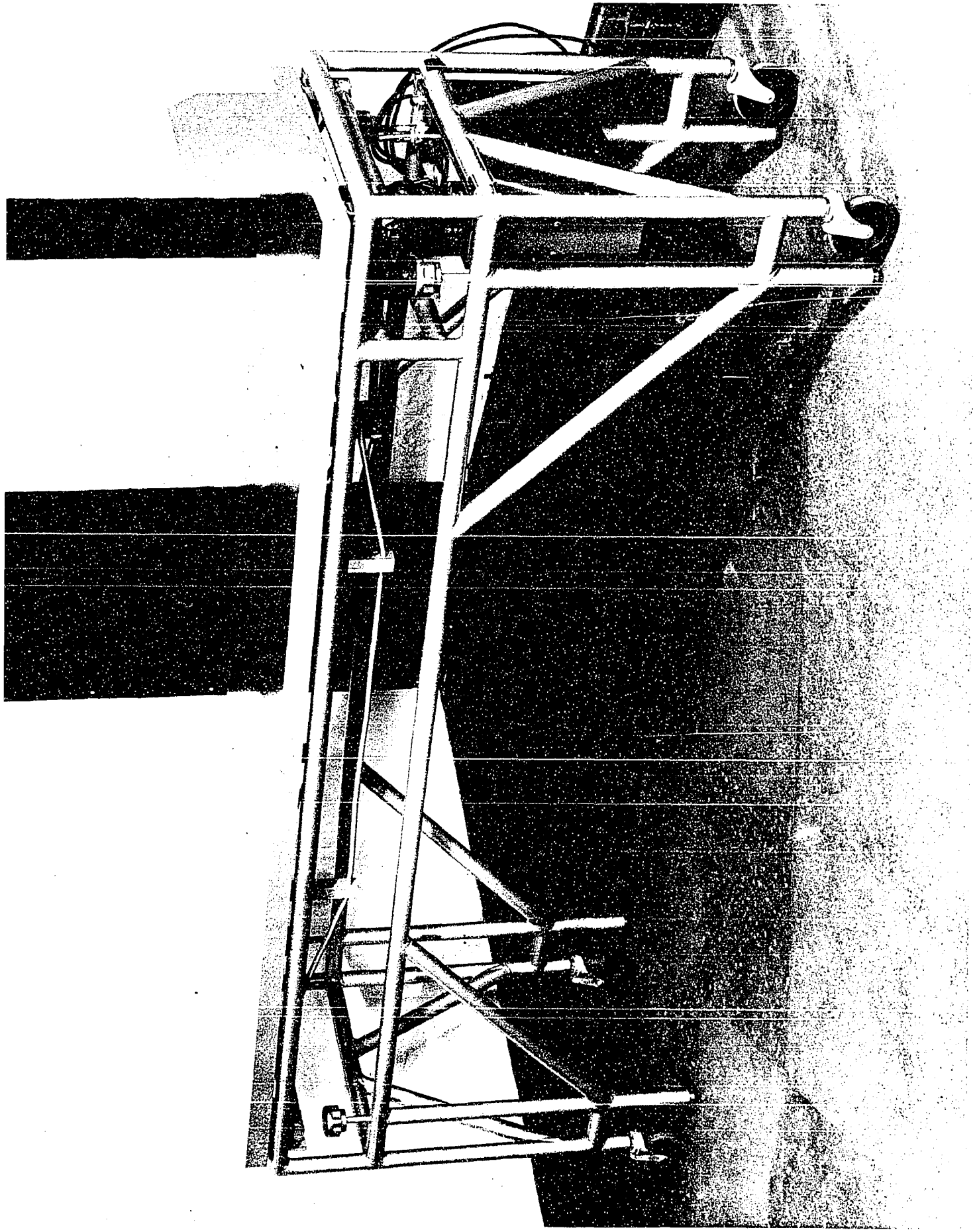


Figure 15.

High frequency commercial instrument (Technitrol Model 128 ballistocardiograph). Courtesy Technitrol Engineering Co.



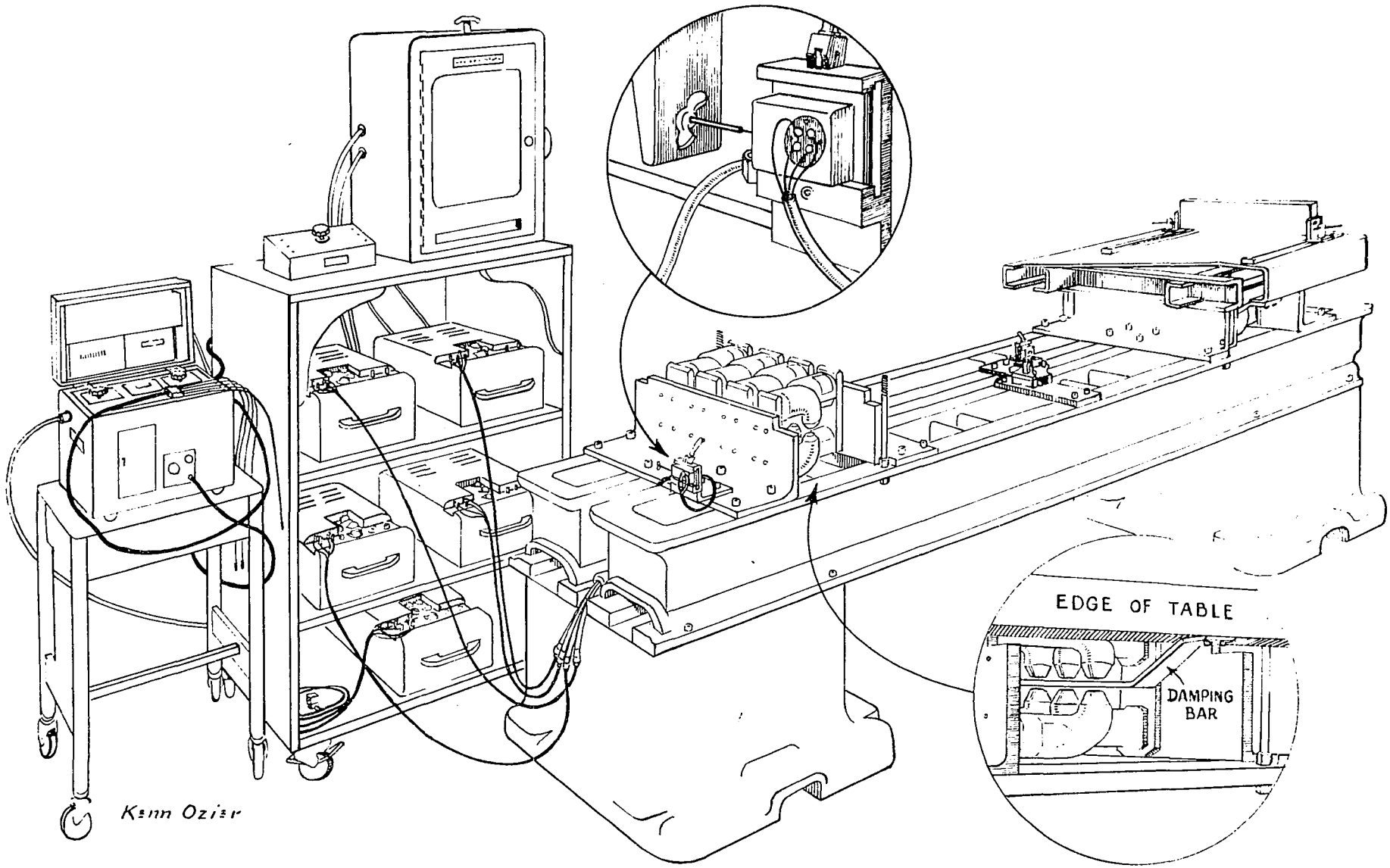
In our laboratory, we have constructed a high frequency research instrument which moves in the frontal plane of the body i.e., it moves not only from head to foot but also from side to side. This motion is obtained by mounting the table top on four rods (Figure 16). Some 10% of critical damping* is added by means of copper bars attached to the top. These move in the magnetic field of a set of permanent magnets. Although this added damping was probably not necessary, since this was constructed as research instrument, we provided it to be certain that we had enough. This instrument weighs something over one ton, and in spite of its mass is extremely sensitive to extraneous vibrations. We have had, as a matter of fact, a good deal of trouble finding a basement room where building vibrations were minimal. Its duplication, for routine work, is not recommended. In this last regard, the commercial instrument described above, although I have had no experience with it, appears to be well designed, and is said to be satisfactory. Anyone with a shop at his disposal and a good mechanic should be able to make a high frequency ballistocardiograph without too much difficulty.

There are only two major pitfalls, and both are avoidable: 1) while the top should be light it must be trussed so that it does not bow in the middle, and 2) any members used in the base must not have a low natural frequency. This last

*For critical damping see page 63.

Figure 16.

High frequency instrument described by Braunstein, Oelker, and Gowdy. The top moves from head-to-foot and side-to-side. Side-to-side motion is recorded simultaneously at three points together with head-to-foot motion.



is most easily avoided by making the base of wood, using 4 X 4 posts and heavy planking.

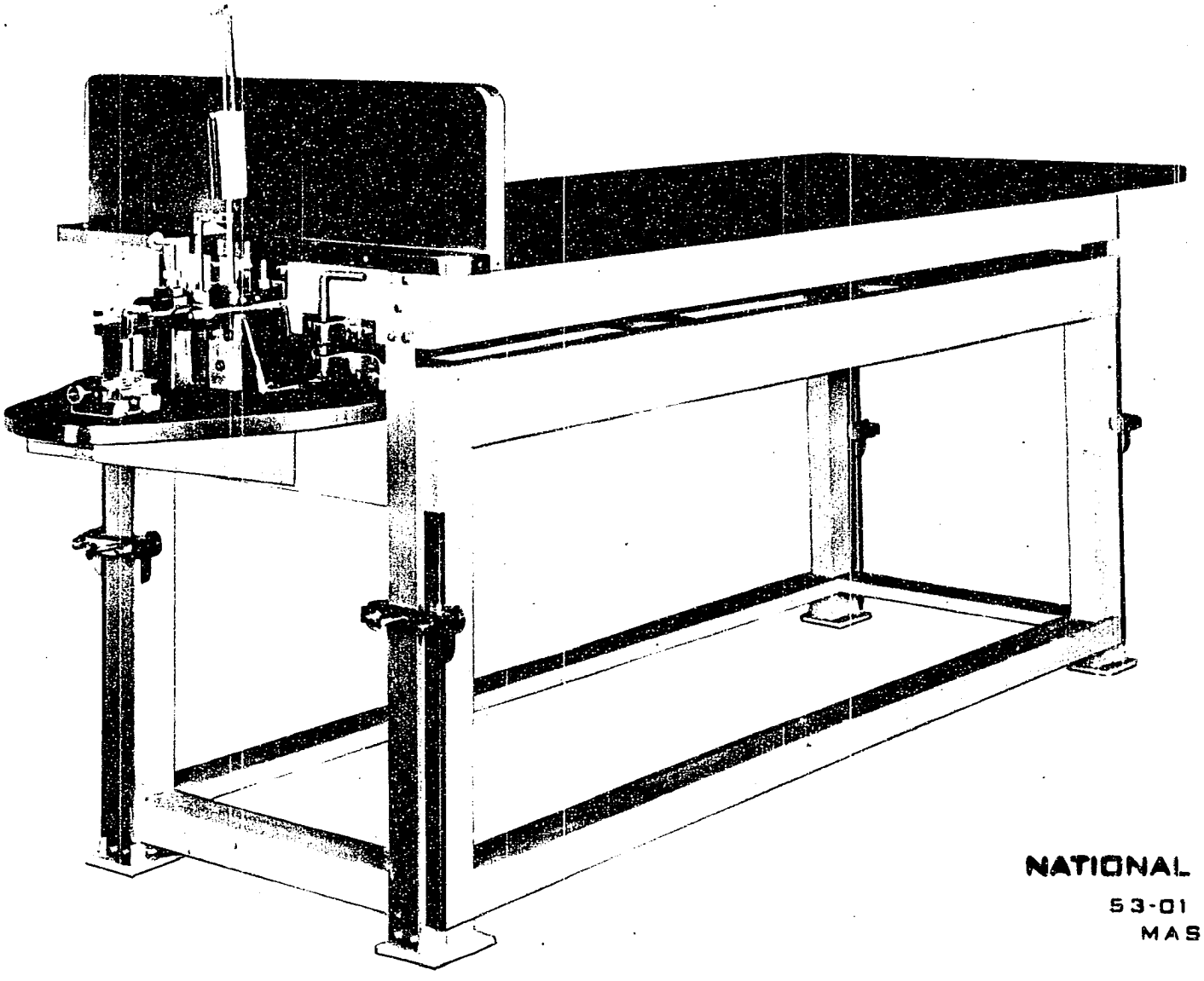
The Nickerson instrument consists of a light table supported on four long springs. This is now available commercially and is illustrated in Figure 17. Riding over the springs are adjustable clamps so that the effective length of the springs can be lengthened or shortened at will. Since the natural frequency changes with the mass, and according to Nickerson's concept should remain fixed at 1.5 c.p.s., the effective spring lengths are so calibrated that the natural frequency will remain constant for given increments. A suitable adjustment can then be made according to the patient's weight. Damping is obtained by means of a sylphon bellows containing oil, and this device, too, is calibrated for different increments of mass to obtain critical damping. The sylphon provides viscous damping* but, since the viscosity of oil varies with temperature, another factor requiring control is introduced.

The third type of instrument now in use was developed by Professor Dock. This too is commercially available and is illustrated in Figure 18. To use it, the patient lies supine on a rigid table; and as he moves back and forth on his own supporting structure, the instrument, which rests on his shins, moves back and forth, too. The motion of the instrument with reference to the table is picked up by a photocell and the

*For viscous damping definition see page 63.

Figure 17.

A commercial instrument of the Nickerson type.



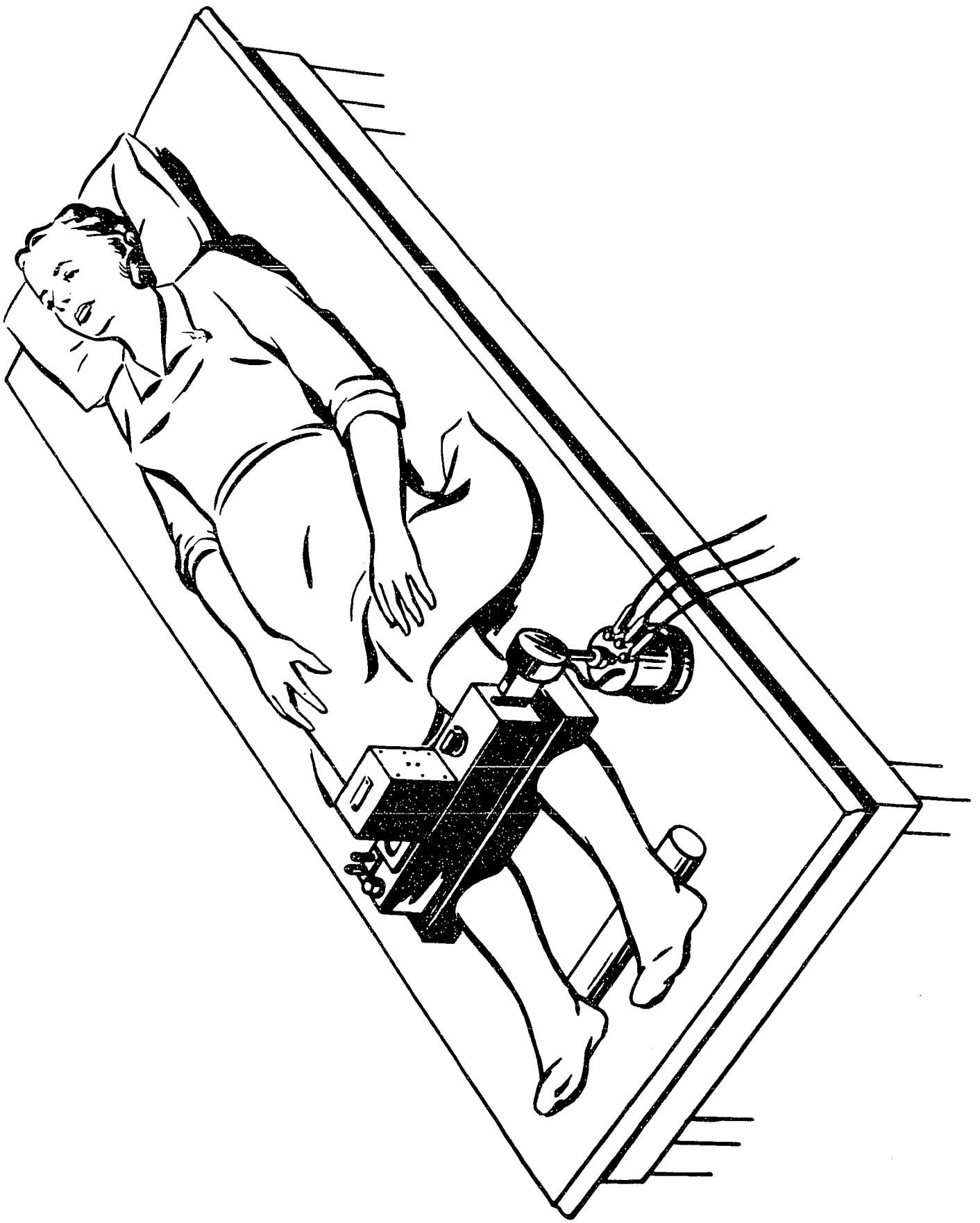
NATIONAL BEMT STEEL CORP

53-01 NURGE AVENUE

MASPETH, L. I., N. Y.

Figure 18.

Commercial version of Professor Dock's instrument. Courtesy of the Sanborn Company.



output fed into a suitable recorder.

We have now considered the three types of instruments in use today. In summary they are: 1) the Starr type with a loaded natural frequency of 10 c.p.s. or higher, and with no added damping, (except in the case of our own research instrument); 2) the Nickerson type in which critical damping and a natural frequency of 1.5 c.p.s. are maintained constant for different increments of mass; and 3) the Dock type which records the motion of the subject as he moves back and forth on a rigid table.

In discussing instruments, it may not be amiss to say a few words about recording; for this aspect of instrumentation can, at times, be extremely exasperating. It might even be said that the type to use depends on the previous experience and temperament of the individual. Most recording devices take off, in one manner or another, the displacement of the table-top, amplify this displacement, and record it against time. Since this is a displacement measurement, it is also a force measurement. Velocity curves, and acceleration curves can also be obtained, but this is not usually done. Most of the earlier instruments employed optical systems with a light source, a mirror activated by the table motion, and a camera with a moving film such as is used in the string electrocardiograph. Starr invented an ingenious link of phosphor bronze on which the mirror was mounted. Nickerson

constructed a pivotal mounting with a high mechanical advantage. Such systems, if properly set up, have a certain reliability about them. The operator does not have to worry about a change in the speed of light. They do not adapt easily, however, to moving the instrument about, require some darkening of the room unless shielded, and possess all the disadvantages inherent in the photographic process.

In the electrical field several devices have been used. The high frequency ballistocardiograph illustrated in Figure 15 employs a pick up built around a R. C. A. 5743 mechano-electric transducer tube which converts displacement into an electrical signal. Other devices used by workers in this field include the capacitance manometer, the strain gauge, (both bonded and unbonded), piezo-electric crystals and high frequency oscillator systems.

In our own laboratory we have used the Statham transducer with satisfaction. This is a linear, relatively inexpensive, and more or less fool proof take off. The input can be supplied by a simple storage battery and the output fed directly into any standard electrocardiograph. For multiple recording as in our research instrument, Figure 16, it is readily adaptable to Brush equipment. So far as direct writing is concerned, the Brush penmotor is quite satisfactory and draws a sharp line. Its only disadvantage lies in the curved coordi-

nates. Most of the direct writing electrocardiographs avoid the curved coordinates at the expense of a tangent error which at full scale deflection may amount to as much as 3%. The new Cambridge direct writer avoids the tangent error most ingeniously by using a vertical writing arm and feeding the paper through a curved trough.

THE BALLISTOCARDIOGRAM
The Complex

We are now ready to take up the ballistocardiogram itself. This term was coined early in his investigations by Starr to describe the record produced by his instrument. At the same time, he labeled the significant peaks and troughs, judiciously picking a portion of the alphabet which would not overlap with the sequence used in electrocardiography. A diagram taken from one of his articles is illustrated in Figure 19. In the convention which he established, an upward deflection on the paper records a headward movement, and a downward deflection a footward movement. Nickerson has used the same nomenclature although his waves occur somewhat later in time due to the heavy damping. The first deflection is an upward one and is called the H wave. It begins approximately at the same time as the intrinsicoid deflection of the electrocardiogram, a fact sometimes useful in its identification, and is followed by a somewhat deeper downward deflection called the I wave. This in turn is followed by an upward deflection usually of still greater amplitude called the J wave. After this occurs a downward deflection, the K wave which is usually as deep as if not deeper than the I wave. Following the K wave are other less important upward and downward deflections labeled in alphabetical sequence which are either damped out

Figure 19.

The normal ballistocardiogram (after Starr).

or obliterated by the next following complex beginning with the H wave.

The genesis of the H wave, the first upward deflection, is still somewhat obscure. At the onset of systole blood is ejected headward in the aorta and pulmonary artery, and the recoil should be footward just as the hand is kicked back when a pistol is fired. However, during the first fifth of systole, the H wave is inscribed and this is in the wrong direction. Nickerson thinks it is caused by auricular systole, and has produced experimental evidence to support his notion obtained on a patient with auriculo-ventricular dissociation. In a study of the time relationships of appropriate complexes he shows that when the qrs of the electrocardiogram is not preceded by a p wave, then the H wave of the ballistocardiogram is not inscribed and the recoil occurs earlier in time. DeLalla and his associates think it is due to a combination of the apex thrust and auricular contraction. On the other hand, it is well known that patients with auricular fibrillation can, and frequently do, have H waves. Also the presence of the large H wave seen in coronary heart disease is difficult to explain. Whatever its cause, it is a complex one; and most careful workers in this field are of the opinion that within the narrow time range of this portion of the ballistic complex there are two or more forces of no negligible

magnitude in action. Regardless of its cause the H wave does obscure the early part of the recoil phenomenon, and this fact has led to some of the severest criticism of the instrument. By this time it is probably necessary only to state that what is left of the footward (and downward) recoil is known as the I wave. With respect to the J wave, here again the situation is complex. As the blood ascends headward, on the pulmonary side it encounters the pulmonary T and fills the pulmonary bed, while on the systemic side a portion continues headward and sideward as the remainder reverses its direction around the aortic arch. The resultant of these forces produces what is probably the most conspicuous single component of the record. Following this J wave, a footward deflection (the K wave) is inscribed. It, in all likelihood, is caused by the abrupt slowing of flow at the end of systole in the lower reaches of the aorta and its branches. Subsequent waves are probably caused by standing waves which are reflected up and down the aorta during diastole. So much for the individual complex.

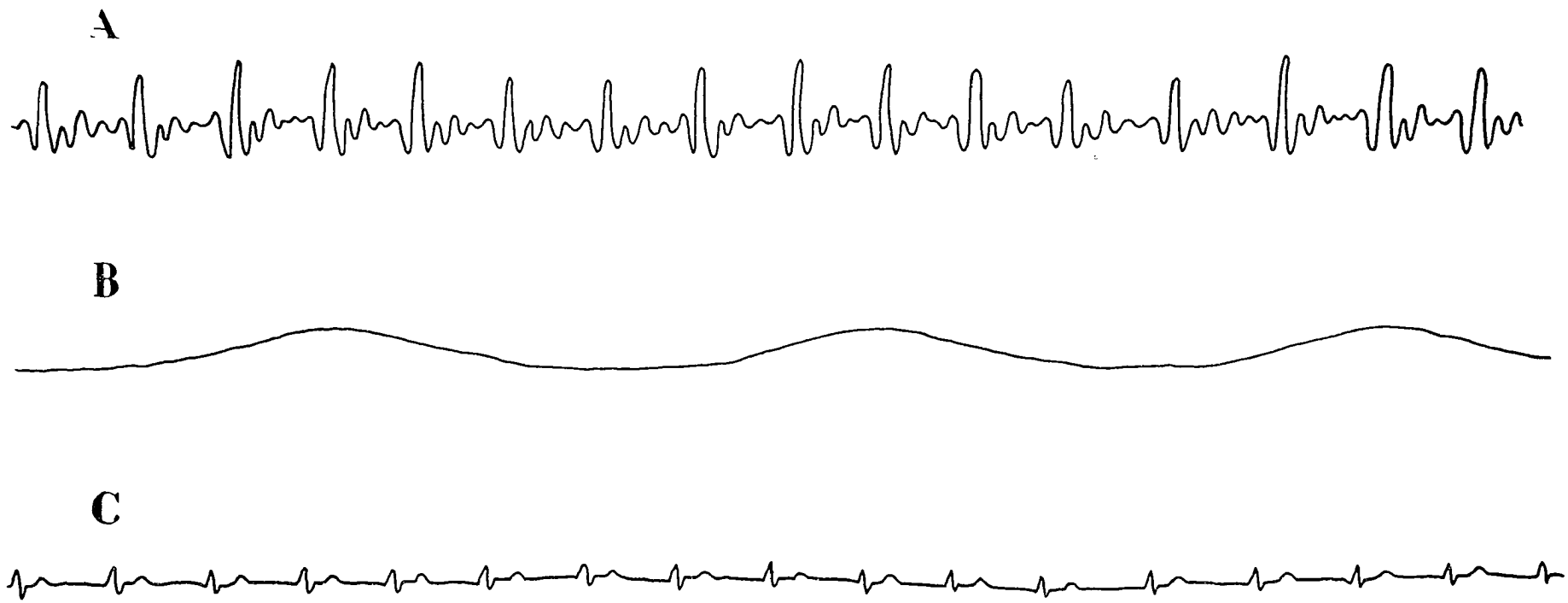
The Respiratory Variation

Let us now look at Figure 20 taken from a strip on which the ballistocardiogram is recorded simultaneously with the movement of the rib cage. We first see that a smooth, undulating envelope could be drawn over the top of the ballistocardiogram passing through the peak of each succeeding

Figure 20.

Portion of a tracing taken on the instrument illustrated in Figure 16.

A Head-to-foot trace
B Pneumogram (upward deflection indicates inspiration)
C Lead I of the electrocardiogram



J wave. We also see that the amplitude of the J wave waxes with inspiration, and wanes with expiration. Closer inspection shows that the amplitude of the I wave follows the same scheme. This phenomenon is usually explained by stating that greater filling of the heart takes place during inspiration since in this phase more blood is sucked into the chest because of the increased pressure gradient. So far as the right heart is concerned this explanation is probably the correct one, and since the introduction of the catheter technique, it has been shown that pulmonary artery pressure with respect to intrathoracic pressure waxes with inspiration, a fact which serves as good supporting evidence. On the contrary, however, the systemic pressure wanes with inspiration, and when it wanes conspicuously at the wrist in partial tracheal obstruction or cardiac tamponade the clinician calls it, unfortunately, a paradoxical pulse.* Furthermore the work of Lauson and his associates at the Columbia Cardio-Pulmonary Laboratory strongly suggests the converse. They hypothesize that in expiration the lungs are squeezed, and blood is wrung out much as water from a sponge. This explanation seems better to fit the facts; and if it is true, the respiratory variation in the head to foot ballisto-

*Every great man has his weak moments. In one of these Kussmaul wrote "I propose, therefore, to call this the paradoxical pulse, partly because of the peculiar disproportion between the heart activity and the arterial pulse; partly because the pulse, in spite of the seeming irregularity, in reality has become a regularly recurring waxing and waning.

cardiogram must be accounted for on the basis of changes in right heart activity, a matter of some importance.

At this point it may seem that the respiratory variation has been highly belabored. If this is so, it is only because of its importance and this is threefold: it must be taken into account in any calculation of cardiac output, a systematic study of corresponding changes in cardiac dynamics may give important clues as to the genesis of the record and finally, clinical ballistocardiographers are accumulating evidence which suggests a large respiratory variation, especially with the degeneration of the wave form in the expiratory phase represents an abnormality of the circulation suggestive of organic myocardial disease.

If I may hazard a guess at this point, I should say that this is so in some cases because the contribution of the right heart to the ballistic pattern in expiration is minimal, and malfunction of the left ventricle is unmasked.

THE ABNORMAL B. K. G. PATTERN

The ballistocardiogram may be abnormal in either of two ways: the complexes, when the record is taken in the resting state, may be too small thus suggesting a decreased basal cardiac output, or the wave form may be abnormal in shape. With respect to the latter, a little reflection will make it apparent that the shape of the curve depends upon the mechanical performance of the ventricular muscle. A healthy young heart contracts with a snap and delivers a good portion of its contents to the aorta and pulmonary artery early in systole. A less vigorous muscle may deliver the same amount of blood, but much of it later in systole. In the first case the complex will be normal (Figure 21 A). In the second case it is apt to be of the so called "late downstroke type" (Figure 21 B). The first case may be compared to the acceleration of a modern automobile with automatic transmission which starts from rest and reaches a speed of thirty miles per hour quickly and smoothly. The second case may be compared to a Model T Ford which also starts at rest and attains a speed of thirty miles per hour somewhat later in time. If both cars have the same mass, at the instant the velocity of thirty miles per hour is attained, then they have the same momentum. A graph in which the velocity is plotted against time, however, will show a great dissimilarity in the way it was attained. Frequently in heart

Figure 21.

A. Normal ballistic pattern
B. Late downstroke pattern
C. Late M pattern
D. Early M pattern

disease we see patterns which are so disorganized that the individual complexes cannot be identified even with a simultaneous E. K. G. Pushing the analogy to the limit, these records suggest the performance of a Model T with one cylinder dead, two performing more or less properly, and a fourth one firing at random. Other patterns which have been described by name are the "early M" type (Figure 21 D) and the "late M" type (Figure 21 C).

The former represents an accentuation of the H wave and is not frequently seen if ever except in coronary heart disease. Neither is its significance well understood. The "late M", however, denotes lack of synchronism in the contraction of the two ventricles and is characterized by a double J peak. It is seldom seen in bundle branch block, for here the time course of contraction between the two ventricles is usually insufficient to notch the J wave. It is usually seen when one ventricle ejects its blood in more or less normal fashion and the other ventricle ejects the majority late in systole.

At this writing the normal ballistocardiogram has not yet been well defined. Hoffman and his associates have more or less quantitatively defined abnormal patterns as grade I, II, III, IV taking into account variations in the minute volume with respiration. Gubner and his group using the Dock instrument have presented standards for various portions of

the complex with reference to time, amplitude and form as well as their relation to the E. K. G. and phono-cardiogram. Jones using the Nickerson instrument has timed various portions of the ballistic complex with reference to the electrocardiogram.

Much remains to be done. Velocity curves in the human aorta and pulmonary artery are not yet available. The effect of changes in pulmonary artery pressure and systemic pressure on the ballistocardiogram remain to be investigated, the damping imparted by the body is imperfectly worked out, and its variation from subject to subject not known at all. These are only a few of the fundamental problems remaining. At first, investigators were only appalled at the complexity of the problem. Now the condition has begun to change, and systematic investigations on various portions of the problem are underway in different laboratories. In our own laboratory, for example, we are attempting to apply a known force directly to the heart muscle itself, and then record the response of the table to this force. If we are successful in the endeavor and can find an equation for the curve obtained, then for a given ballistocardiogram we can find the magnitude of the force acting at any instant. Such an approach is not without experimental difficulty, and the calculations are lengthy and tedious. Yet it is an example of the type of work which, if successful, should do much to improve our understanding of the ballistocardiogram and make it a more useful tool.

CARDIAC OUTPUT

Henderson observed that the size of the ballistic pattern was related to the cardiac output; and later, following this lead, Abramson set up formulas for its calculation which were later shown by Starr to be untenable. Formulas for the calculation of cardiac output have been presented by both Starr and Nickerson. These depend on the Law of the Conservation of Momentum, a combination of Newton's second and third laws which, in simple terms, states that after impact there is no loss of momentum in a closed system. Hence (if there were no H wave) the I wave representing the recoil to headward ejection by both ventricles should be equal and opposite. Since momentum = $m\bar{v}$ then,

$$m\bar{v} = (m_1 + m_2)\, U$$

where m is the mass of ejected blood; $\bar{v}$ the average velocity of the blood; m_1 the mass of the subject; m_2 the mass of the table; and U the average velocity of the table top. Unfortunately for for such a simple solution the first portion of the recoil curve is obscured and $\bar{v}$ only represents an average figure. Velocity curves in the aorta and pulmonary artery are not available for man, and Machella's aortic velocity curve obtained on a dog was obtained on a subject with rapid rate, open chest, and probably in shock.

Nevertheless, as Nickerson has shown, if the aortic

cross-section, A, is known

$$\bar{v} = \frac{S}{At}$$

where S is the stroke volume and t the duration of systole. Substituting an expression for force, F, in place of $\bar{v}$ this becomes

$$S = K\sqrt{\frac{ARt}{T}}$$

where K is a constant and T is the time between the I and J peaks. Instead of this equation, Starr has used an empiric one based on the above, and his working equation becomes

$$S = 33\sqrt{2(\int I\,dt + \int J\,dt)\,A\sqrt{c}}$$

in which Idt and Jdt are the areas under the I and J wave respectively in millivolt-seconds. Later, because of criticism in the method of estimating the aortic cross-section, Starr eliminated this quantity from his formula and increased the numerical value of the constant in front of the square root sign. Nickerson using the same general approach assumed that the ejection velocity would vary in some general way inversely with the pressure opposing it. He also found from a study of Bazett's work that the linear dimensions of the aortic area are proportional to the height of the subject. Hence his formula becomes

$$S = \frac{KF\sqrt{\frac{p_s + p_d}{2}}}{TL}$$

where p_s is the systolic pressure; p_d the diastolic pressure; L the length of the subject; and K the constant determined by

the calculation against the direct Fick.

Neither of these formulas has proved to be too satisfactory when compared with the direct Fick. Cournand found that values obtained with the Starr formula were approximately 18.5% low, and that even with this correction values obtained were much too high on patient in shock. Otherwise the agreement is good. Nickerson's values vary within - 25% on normal subjects, and are much worse on subjects with heart disease. Hence the formulas available today leave something to be desired. Starr has expressed dissatisfaction with his own formula; and using a statistical approach has related it to a deviation from known normals, percentagewise rather than in absolute values, much in the same fashion as is used in the expression of the basal metabolic rate. In the past year he has published the results of a new approach based on a series of ingenious experiments in which he injected the aorta and pulmonary artery of a series of cadavers against known pressures. In these experiments he recorded simultaneously the ballistocardiogram and the motion of the injecting plunger. From this data he has been able to devise a formula for cardiac strength which, as he points out, is more closely related to the ballistocardiogram than the cardiac output. This is obtained by summing up the amplitude of a large and small I wave and a large and small J wave. The expected cardiac force is then calculated from the

subject's surface area. The difference between the observed and the expected values is divided by the expected force to give the percent deviation. Significance of deviation is found by calculating the critical ratio. Although this approach is most promising, investigators still yearn for a simple and accurate method for determining the cardiac output. Today it is not in sight, at least with this technique; for, as Starr has pointed out, we know enough mathematics but not yet enough physiology.

CLINICAL SIGNIFICANCE OF THE ABNORMAL PATTERN

An abnormal ballistic pattern denotes abnormal cardiac function in a mechanical sense. The heart is an oscillating system, and so are the body and the table. These are coupled one to the other in a complex fashion and when the heart beats normally a normal wave pattern is inscribed. This, of course, is a general statement; and how much dysfunction of the heart muscle must be present before an abnormal pattern is produced no one knows today. As we have already seen, the normal pattern is not yet well defined; and, even if it were, the heavy damping of the system would still tend to obscure minor irregularities. For example, bundle branch block as demonstrated by the electrocardiogram seldom produces a pattern of the "late M" type. The depolarization of one ventricle is delayed by a few hundredth of a second and this is not enough to notch the J wave. A differential in muscle tone between the two ventricles is apparently necessary to produce this pattern.

It would seem that a conspicuously abnormal pattern is a bad long term prognostic sign in an apparently healthy person. In an eight to ten years follow-up on ninety healthy individuals past forty in supposed good health, Starr found that three of the four with abnormal patterns had developed coronary heart disease. Our own experience is more striking if less significant statistically. Shortly after the publication of Starr's follow-up

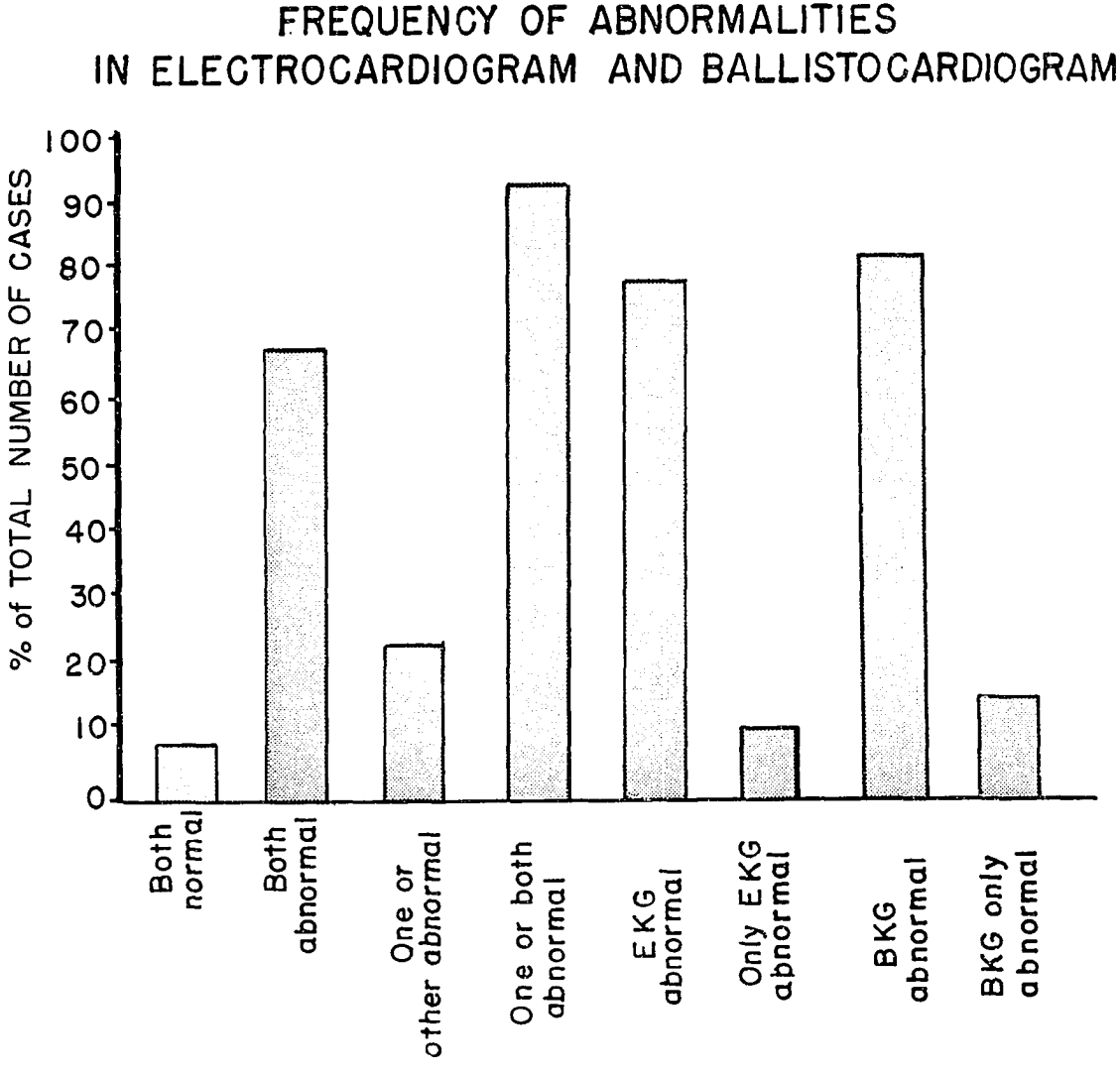
we collected a much smaller series on professors and associate professors from our own medical school. Four had abnormal records. The record of one was grossly abnormal, and this individual died suddenly two days later while sitting in a chair. Two died several years later of carcinoma, and both had old myocardial infarcts at autopsy. The fourth, who is said to have had a normal electrocardiogram at the time, just a year ago developed a massive anteroseptal infarct. He is still alive, but since this experience we have not been anxious to collect records on professors in supposed good health.

An interesting comparison of the incidence of the abnormal ballistocardiogram and electrocardiogram in a free heart clinic can be seen from Figure 22. The data for this chart was compiled from 202 consecutive admissions to the Cardiac Clinic of the Cincinnati General Hospital. Of these admissions, 177 had both records taken and it is from this group that the columns are constructed.

Such a population by and large represents a badly battered group and it is not surprising that 79% demonstrate an abnormal electrocardiogram. This figure is exceeded slightly by the ballistocardiogram which was abnormal in pattern in 82% of the cases. It is also interesting to note that both records were abnormal in 69% of the group and both were normal in 7% thus leaving 24% in which the records did not agree.

Figure 22.

Frequency of abnormalities in the electrocardiogram and ballistocardiogram.



In a way it is surprising that the agreement is as good as it is since the two instruments record such widely diverse activities of the heart. In a group not so heavily loaded with organic heart disease it might be anticipated that the agreement would be considerably less, and hence the use of both instruments would prove of considerable value in the detection of early organic disease. Even in the clinic group, by employing both techniques, the incidence of one or both being abnormal was increased by approximately 10%.

In this regard a highly significant study of the ballistocardiogram and electrocardiogram in coronary artery disease has been made recently by Baker, Scarborough and their group working at the Johns Hopkins Hospital. These investigators carefully studied a selected group of 110 patients some of whom suffered from angina pectoris alone. Others in the group gave a history of myocardial infarction more than six weeks old. None had an abnormal X-ray or a blood pressure over 170/110 mm. Hg. Their combined data may be seen in Figures 23 and 24. Here it will be noted that the divergence between the two techniques is considerable and, although these investigators interpret their results cautiously, the ballistocardiogram appears as an instrument of real value in supplying objective evidence of chest pain when this is due to arteriosclerosis of the coronary arteries.

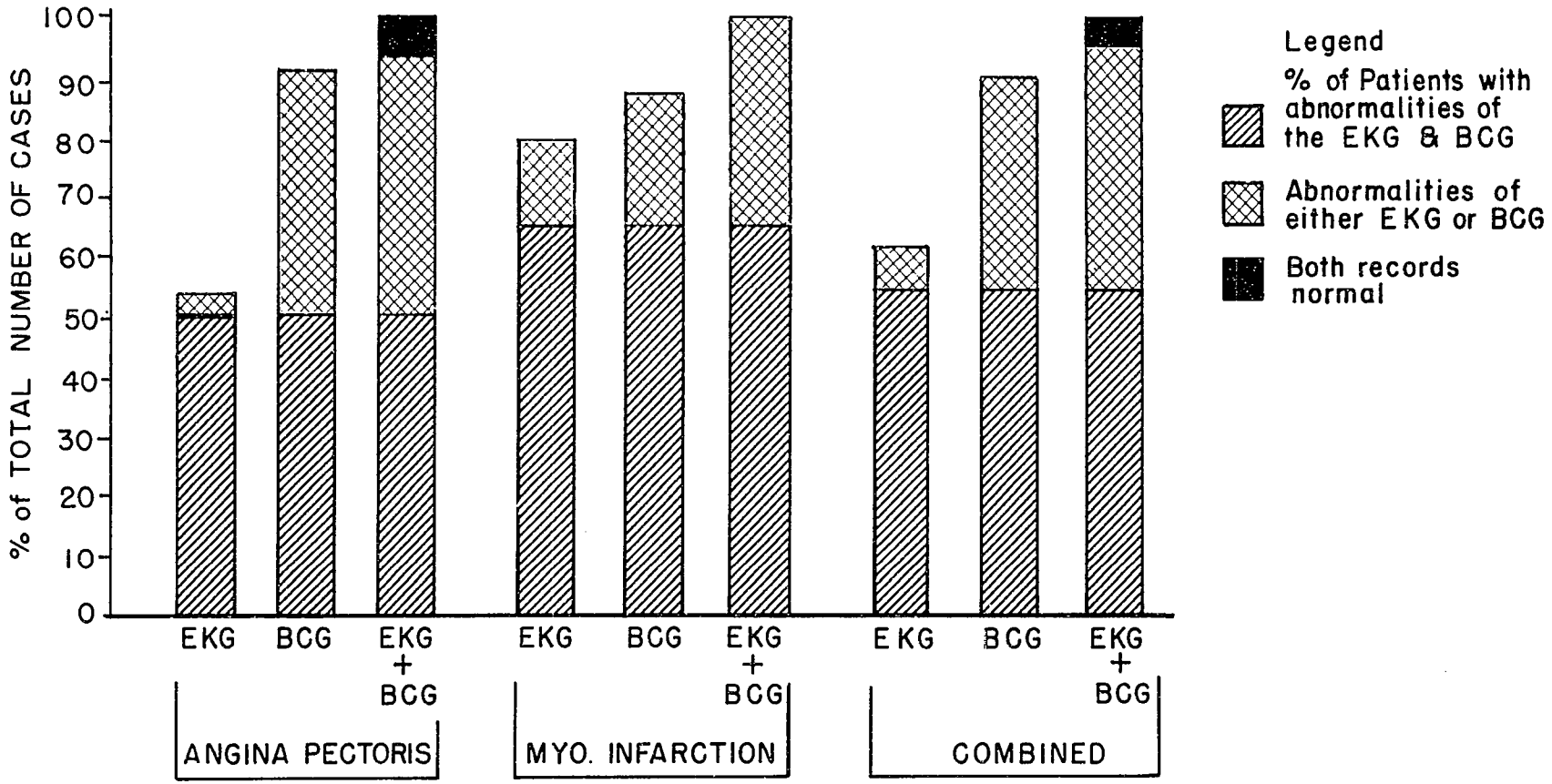
Before leaving the subject of coronary heart disease

Figure 23.

Analysis of diagnostic methods in coronary artery disease. Abnormal and borderline values. (After Baker, et al.)

ANALYSIS OF DIAGNOSTIC METHODS IN CORONARY ARTERY DISEASE

after Baker, Scarborough, et. al.



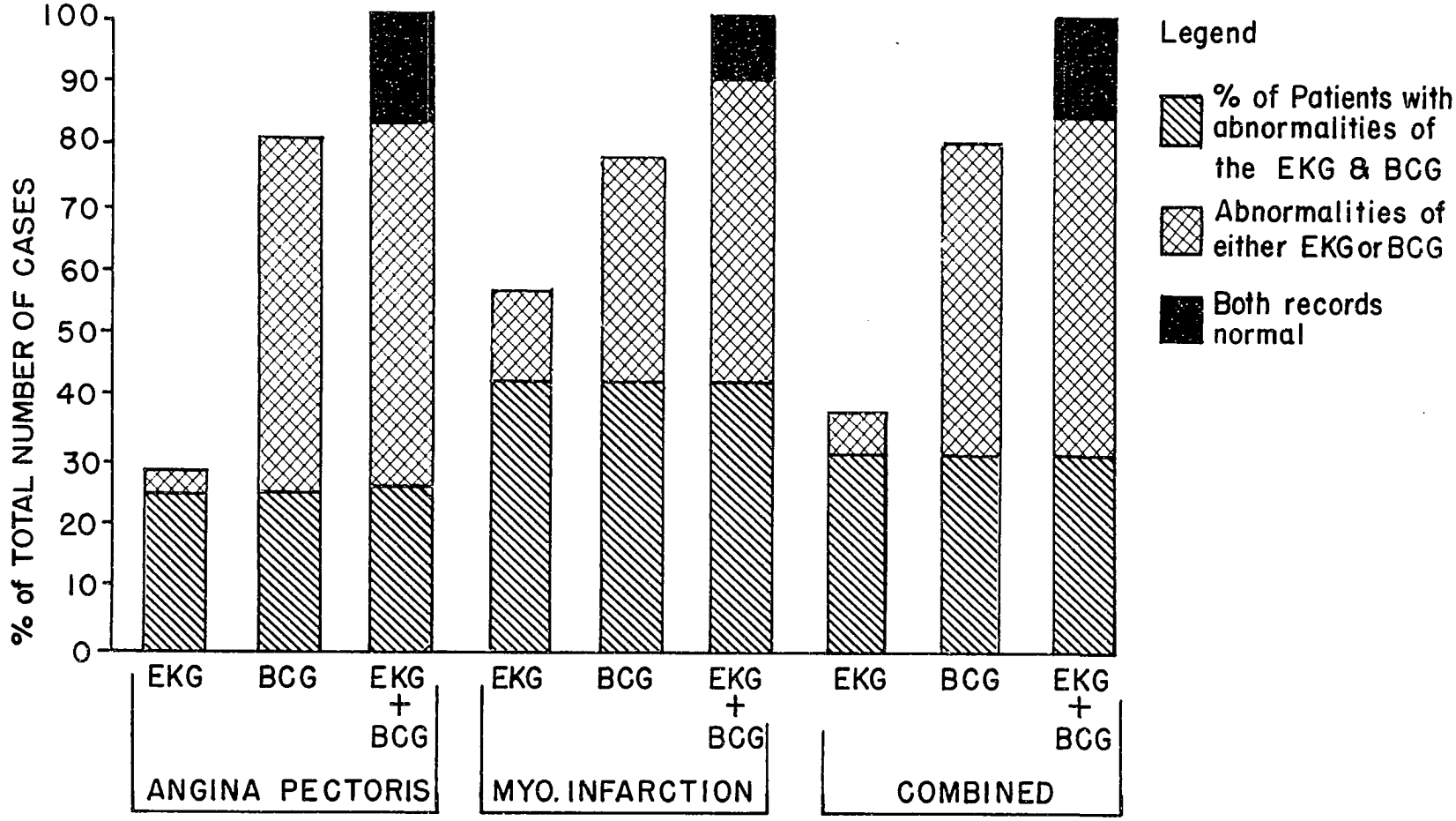
ABNORMAL AND BORDERLINE CASES

Figure 24.

Analysis of diagnostic methods in coronary artery disease. Abnormal values. (After Baker, et al.)

ANALYSIS OF DIAGNOSTIC METHODS IN CORONARY ARTERY DISEASE

after Baker, Scarborough, 'et al.



ABNORMAL VALUES ONLY

it might be well to mention that occasionally a patient is seen with a normal pattern after a minimal myocardial infarction. Usually the electrocardiogram becomes normal or nearly so. These patients usually do well.

With respect to valvular disease it should be mentioned that this in and of itself does not appreciably alter the ballistic pattern. Such is often the case in young patients with mitral stenosis in whom damage to the heart muscle is small. In aortic regurgitation the complexes are large but not necessarily deformed. The only diagnostic pattern, so far as I know, is that of coarctation of the aorta. Here the K wave drops out as would be expected since it is caused by slowing of the blood in the lower aortic region; but even here the absence of a K wave must be weighed since other shunts may produce the same effect even though they are rarely encountered.

In summary, then, it would appear that

1) patients with myocardial disease usually have an abnormal ballistic pattern

2) an abnormal ballistic pattern in an otherwise normal patient is a bad long term prognostic finding

3) an abnormal pattern is an excellent objective finding in patients suffering from symptoms caused by coronary artery sclerosis

4) an absent K wave is almost diagnostic of

coarctation of the aorta

5) valvular disease in and of itself does not appreciably affect the ballistic pattern

6) an abnormal pattern tells us only that we are dealing with abnormal mechanical function. This information is valuable when properly fitted into the overall clinical picture.

CLINICAL SIGNIFICANCE OF THE ABNORMAL OUTPUT

The ballistocardiogram is usually recorded when the patient is rested and in the post-absorptive state. Hence if the patient's height and weight are known the cardiac index can be calculated. This is usually expressed in liters per minute per square meter of body surface. Starr has published normal values for both sexes, and has investigated conditions in which the output is too great or too little. The first he calls hyperkinemia; the last hypokinemia. These are excellent physiological terms and are worthy of more widespread use than they enjoy today. His data is illustrated in Figures 25 and 26. The two cases of beri-beri heart disease which we have studied fall in this group.

Figure 25

Occurrence of Hyperkinemia

Group	Frequency of hyperkinemia among all cases in the group
Healthy persons	A very few
Hyperthyroidism without cardiac complications	Almost all
Extreme emaciation	About ¾
Patent ductus arteriosus	Most
Peripheral A-V aneurysm	Few
Anemia	About ¼
Febrile disease tested late in course	A few only
Hypertension	A very few
Pulmonary	
After pneumonectomy	4 or 5 cases
In chronic disease	A few
Essential hyperkinemia	20 cases

Figure 26

Occurrence of Hypokinemia

Group	Frequency of hypokinemia among all cases in the group
Moribund patients	All
Shock	All
In congestive heart failure	Most
Valvular heart disease not in failure	About $\frac{1}{2}$
Coronary heart disease:	
Chronic angina pectoris	Almost all
Soon after infarction	About $\frac{1}{2}$
Hypertension	About 1/3
Endocrine diseases:	
Myxedema	All
Pituitary or adrenal	Many
Convalescence from severe febrile disease	About $\frac{3}{4}$
Essential hypokinemia	26 cases

It will be noted that in his hypokinemic group which represents 100 cases, 26 showed no disease to which it could be attributed. In the hyperkinemic group of 100 cases this occurred in 20 cases. Thus he demonstrated objectively two distinct groups in which the physiological response of the circulatory system is not normal. Such patients are usually classified by the clinician in some such wastebasket as neuro-circulatory asthenia, or cardiac neurosis; and are worthy of carefully controlled psychological study. The instrumentation for it is obviously available in the ballistocardiograph. It is also known that anxiety of a certain type will increase the cardiac output. This has been

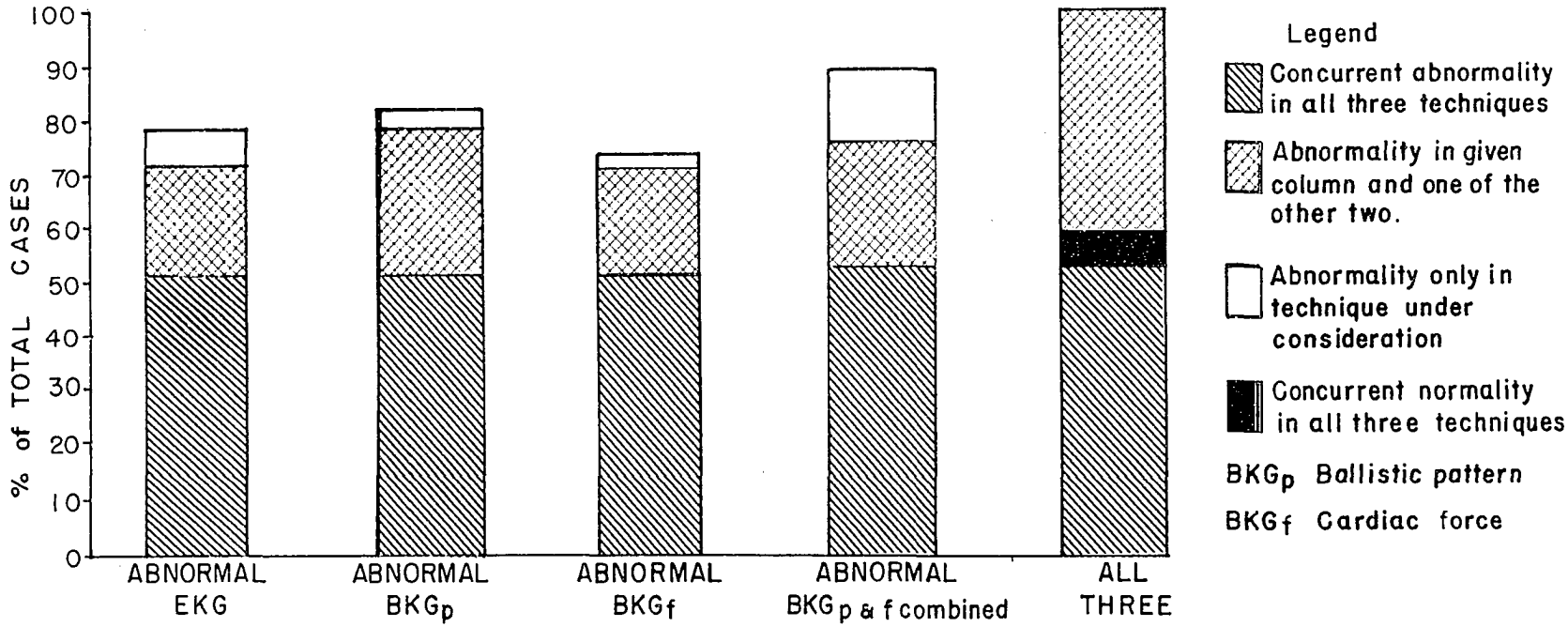
beautifully shown by Hickam, Cargill and Golden who studied a group of senior medical students before and after an important examination.

Unfortunately the cardiac output cannot be calculated when the ballistic pattern is abnormal since no formulas are as yet available. However, Starr has recently developed a formula for the calculation of initial cardiac force. This has already been discussed. It does not require a normal pattern and can be applied to all records. We have found the calculation most valuable in evaluating ballistocardiograms on patients whose patterns were questionably borderline. The results when this calculation was applied to the group of patients from the Cardiac Clinic of the Cincinnati General Hospital mentioned in the previous chapter are illustrated in Figure 27. When taken alone it can be seen that this calculation, when abnormal, does not appear in as high a percentage of these patients as an abnormal pattern. When combined the percentage is increased. The calculation may well prove of special value in patients with disease of the coronary arteries since many of these have small abnormal complexes from which the cardiac force can be calculated although the cardiac output cannot. For example, Dr. Bernard Berman and I several years ago collected data on a series of patients with angina pectoris before and after a large meal. We collected both ballistocardiograms and electrocardiograms.

Figure 27.

Frequency of abnormalities in electrocardiogram, ballistic pattern and initial cardiac force.

FREQUENCY of ABNORMALITIES in EKG BALLISTIC PATTERN & INITIAL CARDIAC FORCE



Since most of the ballistocardiograms were of abnormal pattern the cardiac output could not be obtained.

It was interesting to note, however, that in the few which could, the expected increase of about 25% did not occur. This experiment was, in essence, an exercise tolerance test; and there will undoubtedly be much work of this type done in the future. Makinson has recently published an article in which he recorded ballistocardiograms before and after the two-step test. This test gives, as he points out, additional information in three ways: 1) the normal increase in cardiac output may not take place; 2) the response may be excessive; or 3) the form of the record may become abnormal after exercise.

Brown, Hoffman, and De Lalla, noting a large respiratory variation in patients with angina pectoris, have calculated the cardiac output for each phase of respiration and have developed a formula for expressing it. This is as follows:

R. V. I. (Respiratory Variation Index) =

$$\frac{\text{Largest Inspiratory Minute Volume} - \text{Smallest Expiratory Minute Volume}}{\text{Surface Area in Square Meters}}$$

All of their normal controls were found to have an R. V. I. between zero and 450 cc. per minute per square meter of surface. In a series of 21 patients with typical angina all had R. V. I.'s in excess of this figure. Like Baker and Scarborough in their study of abnormal patterns, it should be noted that

Brown and his associates may well be developing a valuable approach in the study of coronary artery disease. It should also be noted that they have taken advantage of the sensitivity of a technique which records changes with each heart beat, a characteristic which has yet to be fully exploited in the study of cardiac physiology. This presents no threat to the patient, and requires only that he lie quietly on the table. The ballistocardiogram has much to offer today. When it is better understood, it will offer a great deal more.

APPENDIX

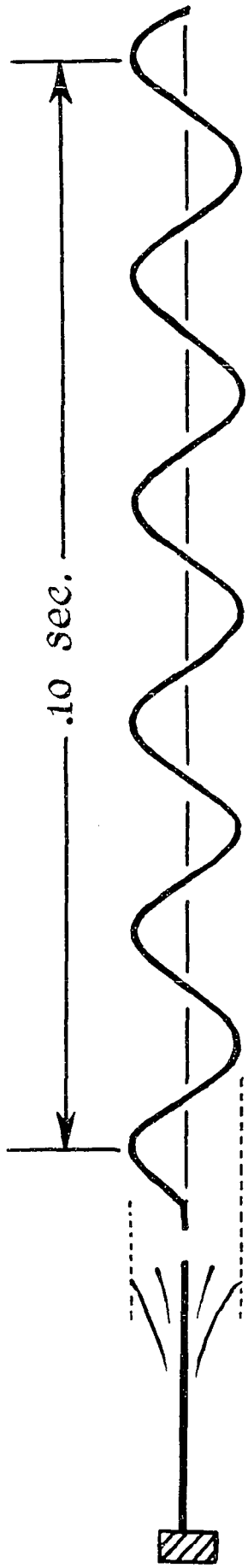
As Dr. Hamilton has so drily and aptly put it, "The forms which the apparatus takes are as diverse as the minds of the men who construct them". Hence it may be worth while to review a few of the fundamentals of vibrating systems if we wish to evaluate a given instrument.

Natural Frequency: Let us first take a simple spring fastened securely at one end. If the other end is then plucked with the finger (or struck with a mallet if it is stiff), and then allowed to vibrate freely, a photograph of its motion taken at right angles on a moving film (assuming no loss of energy) will appear as in Figure 28. You will notice that the distance between any two peaks is the same. In this observation you have discovered a fundamental property of the spring, its natural frequency (f_n). In Figure 28, six peaks (five intervals of time) are counted out for 0.10 seconds. Hence the natural frequency for this particular spring is 50 cycles per second (c.p.s.) and once determined will remain constant. If you wish to make the natural frequency higher, you may make the spring thicker or shorter. If you wish to make it lower, then you may make it longer, thinner or weight the end. This last device is often used in the design of tuning forks.

Damping: Let us look again at Figure 28. After the spring is plucked, the amplitude of succeeding vibrations remains

Figure 28.

Undamped sine wave.



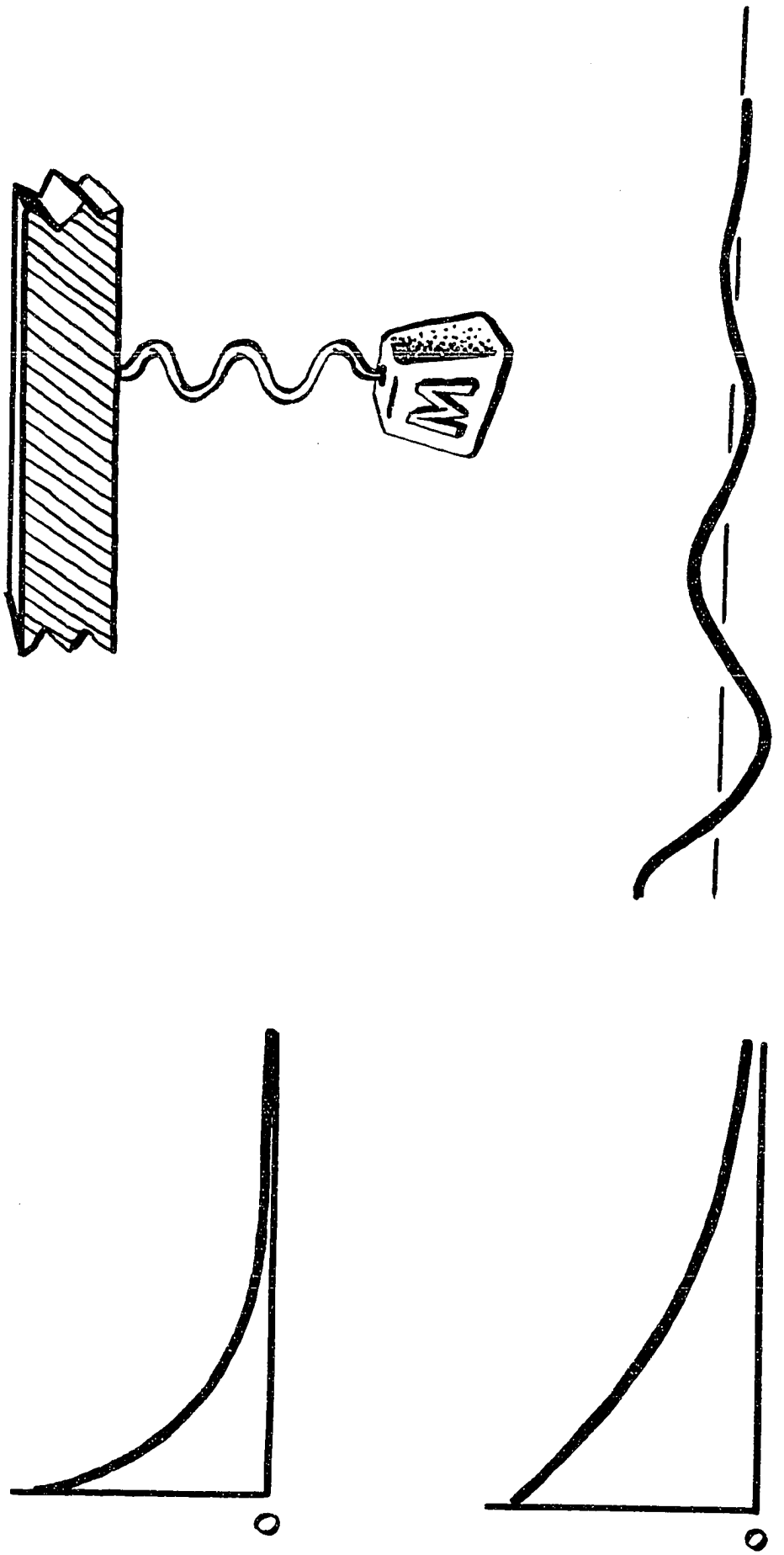
the same since no energy is removed. This is an ideal case. Actually, however, the amplitude of the succeeding vibrations will diminish as in Figure 29, lower right. This phenomenon is known as damping. By means of various mechanical and electrical devices energy can be removed from the system more quickly, and the amount of damping increased. If this is increased to the point where the spring returns promptly to the base line without oscillating (Figure 29, upper left), it is known as critical damping. If, on the other hand, the spring returns slowly to the base line as in Figure 29, lower left, it is said to be overdamped.

The concept of damping is an important one, since the body alone adds about 50% of critical damping to the ballistic system, a point to be discussed later. Furthermore, some instruments have mechanical or electrical devices attached to the moving top in order to obtain added damping. Any damping so added must be proportional to the velocity (so called viscous damping) in order to yield to convenient mathematical analysis. For the coefficient of this property we shall use the symbol C and for critical damping the symbol C_c.

Spring Constant: Let us now take a mass M (Figure 29, upper right) which is free to move up and down only. The force required to displace M one unit of length is known as the spring constant for which we shall use the symbol K.

Figure 29.

Upper left: Critical damping
Lower left: Overdamping
Lower right: Underdamping
Upper right: Simple mass suspended by a spring



Impressed Frequency: If the mass in Figure 29, upper right, is shaken up and down by an external force, a little reflection will make it apparent that the amplitude of the response will depend on this force. Now it so happens that the frequency of the forced vibration depends only on the frequency of the shaking force (for this we shall use the symbol F). The amplitude A, however, depends not only on the magnitude of the shaking force, but also on the ratio of its frequency to the natural frequency of the system. Hence it becomes unmistakably evident that, if the ballistocardiograph is to reproduce accurately the forces acting upon it, this ratio will have to be carefully investigated.

Resonance: When the ratio of the frequency of the shaking force to the natural frequency becomes 1, resonance is said to exist. The amplitude of successive vibrations builds up rapidly, and hence is most undesirable. This is the reason why soldiers break step when crossing a bridge; for, if the frequency of the march step should happen to coincide with the natural frequency of the bridge, the structure might well collapse. In our case we are not particularly worried about the ballistocardiograph disintegrating because of the patient's heart beat (although this is theoretically possible) but, as stated above, we are interested in a measuring instrument that will accurately reproduce the forces acting upon it.

Phase Angle: Harmonic motion is the simplest form of periodic motion, and most vibrating systems move in approximately this fashion. Now harmonic motion is a sine or cosine function, and may be written as $x = X \cos \omega t$ when the angular velocity, ω, is a constant $(2\pi f)$, and ωt an angle measured in radians. Consider the curves in Figure 30.

The angular period for both of these curves is $\frac{2\pi}{\omega}$ or 360°. Now, if we take

(1) $$x = X \cos \omega t$$

as the reference curve, then

(2) $$x = X \sin \omega t = X \cos \left(\omega t - \frac{\pi}{2}\right)$$

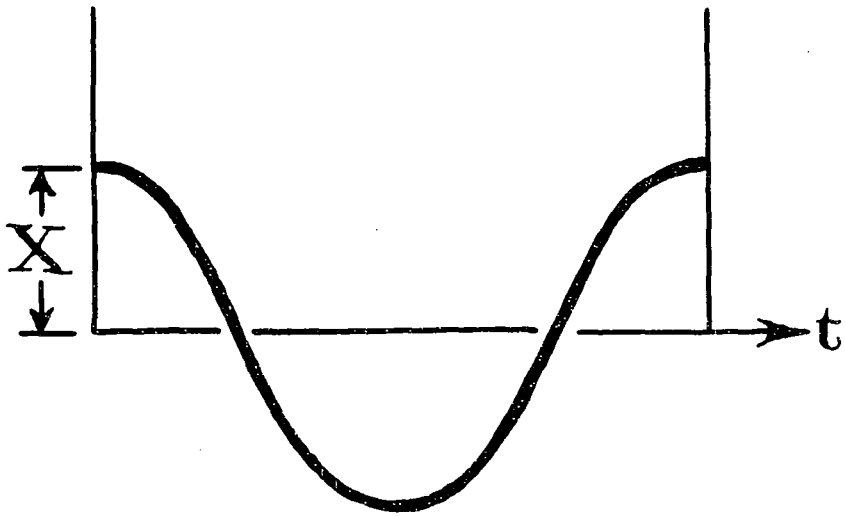
Curve 2 is $\frac{\pi}{2}$ radians or 90° out of phase. It can also be seen from inspection, that the maximum of curve 2 occurs one quarter of the length of the base line (90° or $\frac{\pi}{2}$) later than in curve 1.

Equation of Motion: We are now ready to consider the ballistocardiograph as a vibrating system. This has a mass M (which may include the mass of the body), a constraining spring constant K, and a viscous damping force whose coefficient is C. Upon this system is impressed a shaking force which is a function of time F(t). For F(t) we can find two values, one by Fourier's expansion, and the other from Newton's second law. When these are equated each to the other we get an expression for a single term which looks like this

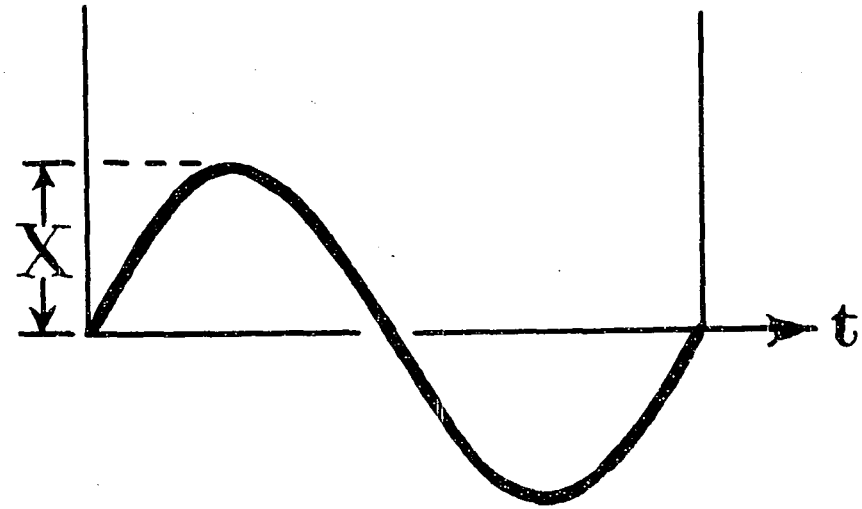
(1) $$Mx'' + Cx' + Kx = A \sin(\omega t + \delta)$$

Figure 30.

Phase relationships of the sine and cosine functions.



$$x = X \cos \omega t$$



$$x = X \sin \omega t$$

In this equation x" is the acceleration, x' the velocity, x the displacement, and δ the phase angle in the Fourier expansion. We are familiar with the rest of the terms. This expression is a linear differential equation and its solution is known. It may be written

$$(2) \qquad x = \frac{A}{\sqrt{(C\omega)^2 + (K - M\omega^2)^2}} \sin(\omega t + \delta - \phi)$$

in which ϕ is the phase angle between the force and displacement.

If the motion of the table were uncomplicated by the inertia of the table and by the damping, then (putting M = C = 0 in Equation 2) we would have

$$x = \frac{A}{K} \sin(\omega t + \delta)$$

since in this case the angle ϕ by which the displacement lags behind the force also becomes zero. In this case, the displacement would be proportional to the force, with the same constant of proportionality 1/K for all frequencies of the shaking force F(t). This is an ideal case, unattainable in practice. If we put x_d = A/K = the amplitude of this ideal response, we can consider x_d as the "desired" amplitude.

The amplitude of the actual vibration of the table is the coefficient in front of sin ($\omega t + \delta - \phi$) in Equation 2. If we designate this coefficient, which is also the maximum value of x, by x_m; then

$$\frac{x_m}{x_d} = \frac{K}{\sqrt{C^2\omega^2 + (K - M\omega^2)^2}}$$

For free vibrations of our system, the natural frequency, f_n, is given by the relation

$$\omega_n = 2\pi f_n = \sqrt{\frac{K}{M}}$$

and the critical damping, C_c, by the equation

$$C_c = 2\sqrt{MK}$$

Using these equations we can express the ratio $\frac{x_m}{x_d}$ as follows

$$\frac{x_m}{x_d} = \frac{f_n^2}{\sqrt{(f_n^2 - f^2)^2 + 2f^2 f_n^2 (\frac{C}{C_c})^2}}$$

Figure 31 is plotted from this equation, except that the subscript m has been dropped and x has been written instead of x_m.

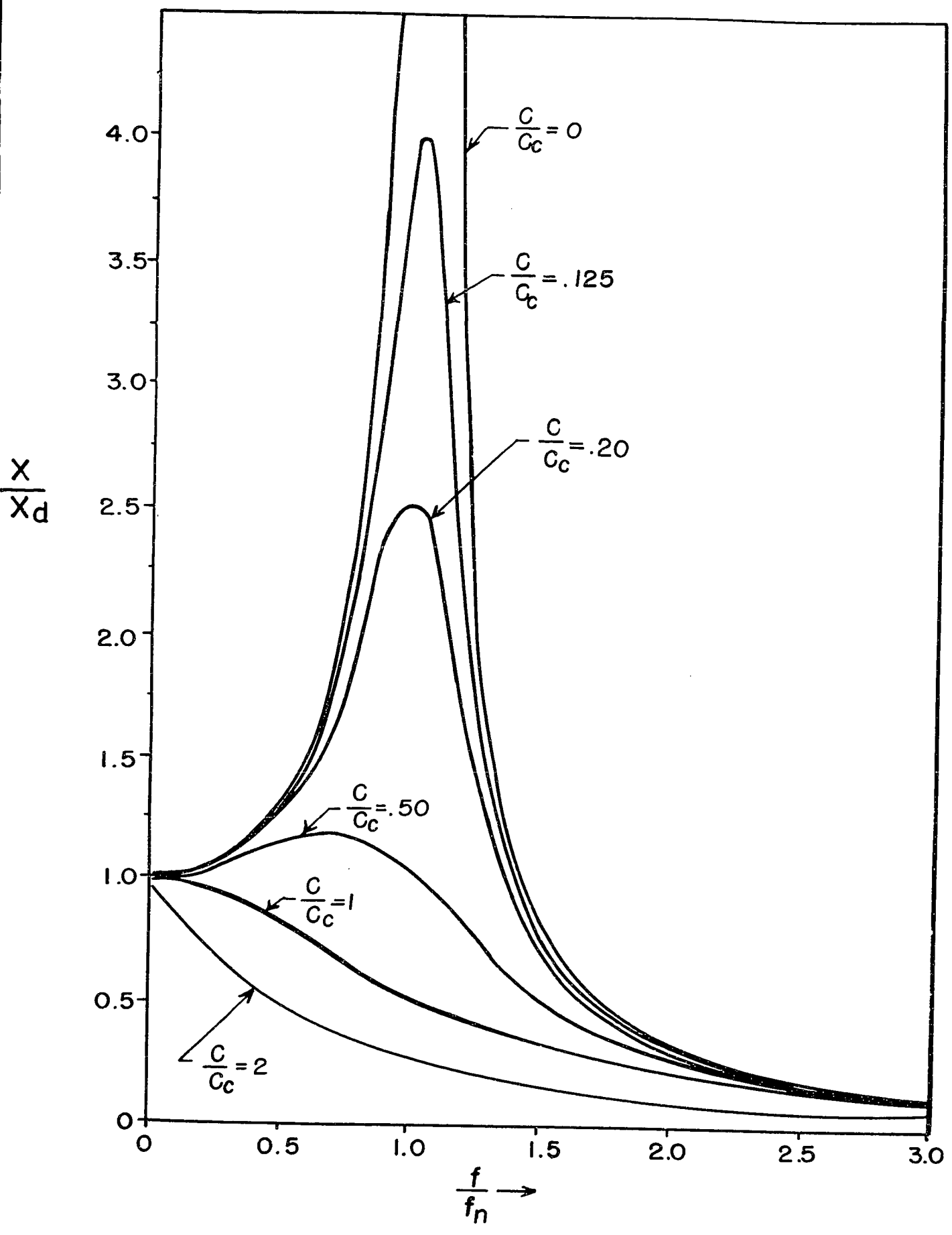
For critical damping $\frac{C}{C_c} = 1$ and the equation acquires a particularly simple form

$$(3) \qquad \frac{x_m}{x_d} = \frac{f_n^2}{f_n^2 + f^2}$$

Let us look at these curves. We first notice that when $\frac{f}{f_n} = 1$, and there is no damping, the curve flies off to infinity. Since x_d is fixed, x has become large. Here we have resonance. Various degrees of added damping tend to pull the

Figure 31.

Ratio of the resultant deflection, x, to the desired deflection, x_d, vs. the ratio of the impressed frequency, f, to the natural frequency, f_n, for various values of the damping ratio.



curve down, but since we may be dealing with some unknown factors this ratio is obviously a good one to stay away from. Let us look at the curve again. Since we are interested in the accurate reproduction that the shaking force impresses on the table we should try to find a range where x/x_d is a constant. Inspection shows that this can be obtained by keeping f/f_n small. If the ratio f/f_n is to be small, since we can do nothing about f, then f_n must be made large. In the equation

$$\frac{x}{x_d} = \frac{f_n^2}{f_n^2 + f^2}$$

since the squares of these quantities are involved the difference between f_n^2 and f^2 will become even greater. In this case f becomes negligible and

$$\frac{x}{x_d} = \frac{f_n^2}{f_n^2 + f^2}$$

which is approximately equal to

$$\frac{f_n^2}{f_n^2} = 1$$

and a straight line relationship is maintained. If, conversely, we reverse the ratio and make f_n smaller than f then again the squares of the quantities will increase, the difference and f_n will become negligible. In this case x/x_d is approximately equal to

$$\frac{f_n^2}{f^2} = \frac{f_n}{f}^2$$

an expression which varies rapidly in magnitude with changes in f. Since f for the living subject cannot be controlled, the inference can be drawn that the natural frequency should be as high as possible, if the system is to reproduce the forces acting upon it as accurately as possible. This may also be seen by inspection from Figure 32.

In Figure 33 the phase angle between the force and the displacement is plotted on the y axis. On the x axis is plotted the ratio of the impressed frequency to the natural frequency. Some five curves are shown for various values of the damping ratio. When f/f_n is 1, resonance is seen to occur. It is also seen that the only opportunity of obtaining a straight line relationship is to move as far to the left on the x axis as possible. Since we have no way of controlling f, then f_n must be made large, and here the inference becomes inescapable that only a high frequency instrument will accurately reproduce the forces acting upon it.

Nickerson and Curtis in considering the design of their instrument took a different theoretical approach. They considered as an ideal case a situation in which the body floats freely in space much as the beautiful lady on the stage appears to float under the magic wand of the magician. They then took as their criterion the ratio of the amplitude of table motion to this ideal case. Here, the system is taken as being without con-

Figure 32.

Ratio of the resultant deflection to the desired deflection vs. the natural frequency, f_n, of the table for various impressed frequencies, f.

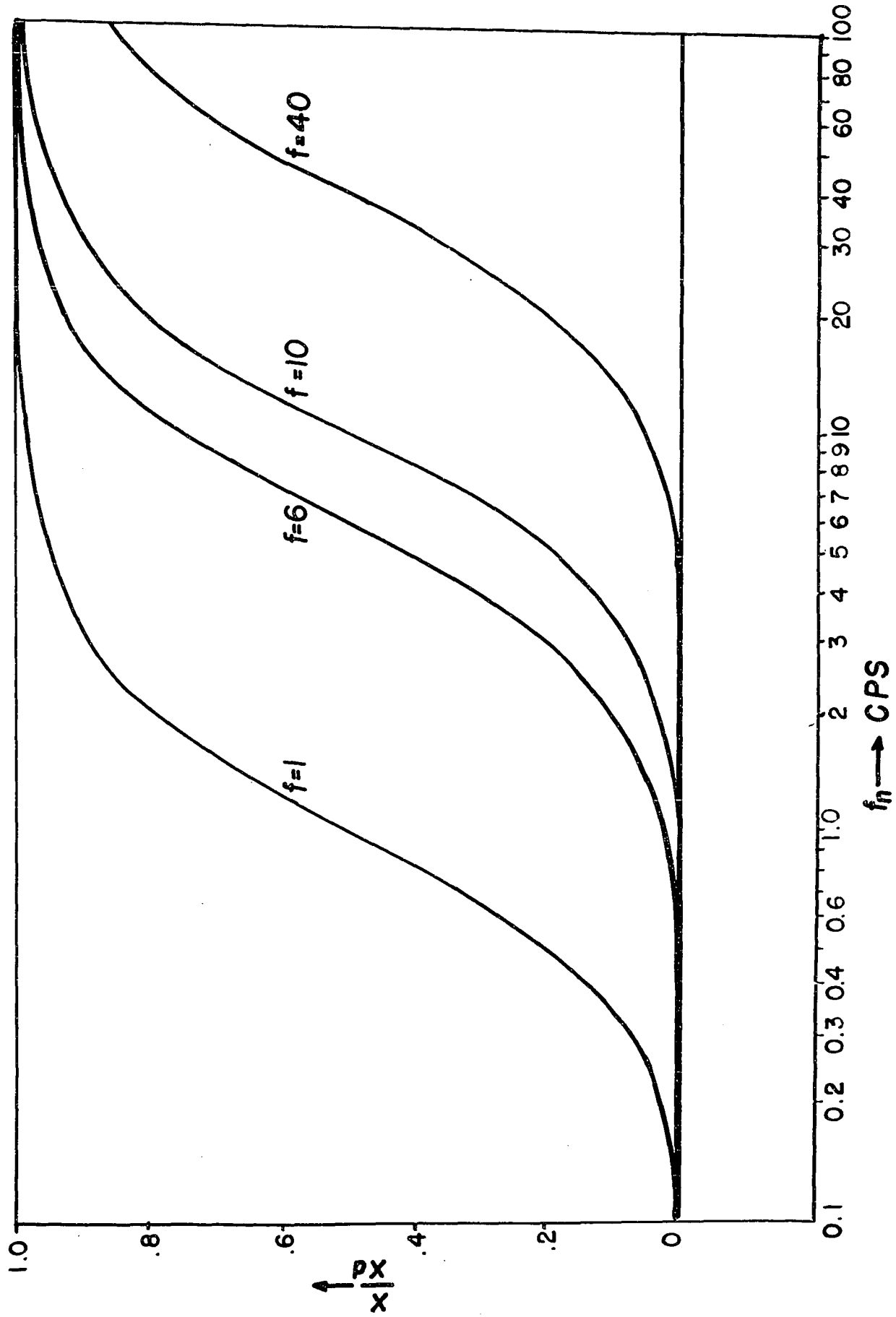
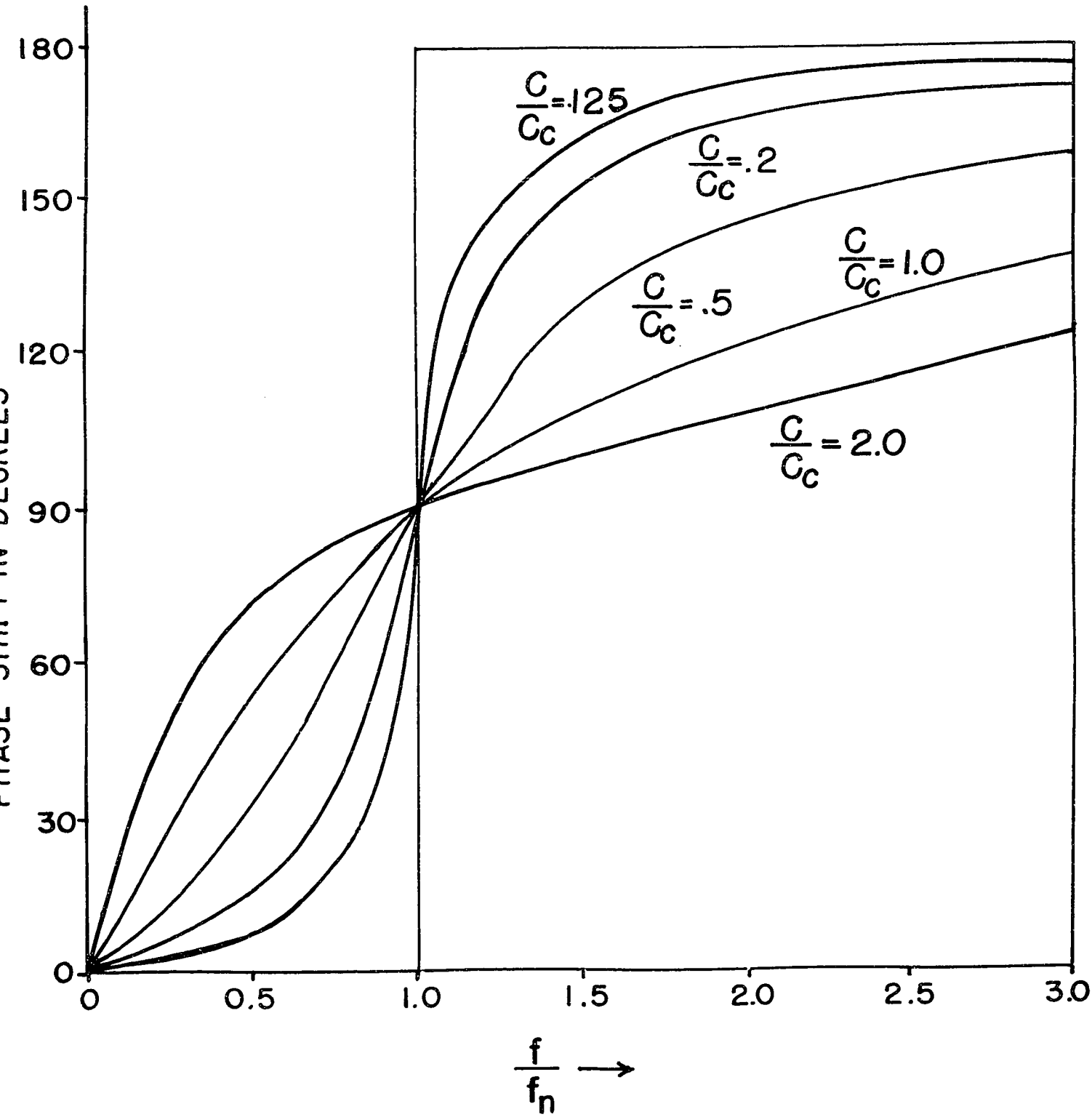


Figure 33.

For various values of the damping ratio, the phase angle between the impressed force and the table motion is plotted against the ratio of the impressed frequency, f, to the natural frequency, f_n.



straint or damping, that is, if we apply equation (1), C and K are both zero and drop out. Then for this ideal case

$$x = \frac{-A}{M\omega^2}(\sin \omega t + \delta)$$

Since $\omega = 2\pi f$ by definition, the amplitude of this motion is not constant for a constant amplitude input, but will vary with f. Since the shaking function will not only change with the heart rate, but probably contains other frequencies too, it would seem that this defect may well be a serious one.

In the Dock instrument, conditions are somewhat reversed. Here the mass to be considered is not that of the table, but of the instrument itself. The spring constant and damping coefficient depend upon the physical properties of the tissues overlying the shins and on which the instrument rests. These will have to be investigated before this instrument can be evaluated.

ADDENDUM

The possible significance of the data from the Cardiac Clinic of the Cincinnati General Hospital presented here was tested in a number of different ways. Correlation between the age of the patient and the deviation from normal cardiac force was attempted by means of the Pearson Product-Moment Coefficient of Correlation and the Correlation Ratio (Eta). The results were inconclusive. A regression equation between the reciprocal of the age of the patient and the force was calculated. The results failed to show any correlation between the two variables. An analysis of variance to test the significance of the differences between the cardiac force of various disease groups was contemplated, but abandoned, since the normality of the distribution of the data and the sampling technique employed to collect it were questionable. It is believed that the last two reasons also influenced the correlation results. Another reason might be that the sample (240 cases) was too small in view of the wide range of both variables.

A relationship between initial cardiac force and the transverse diameter of the heart as seen on PA Teleo Roentgenogram was sought by Tetrachoric Correlation. Again the relationship appeared to be negligible.

The graphical representation of the data used in this thesis was adopted since it was felt to be best suited to the material.

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PART II

THE VECTORBALLISTOCARDIOGRAM

TABLE OF CONTENTS

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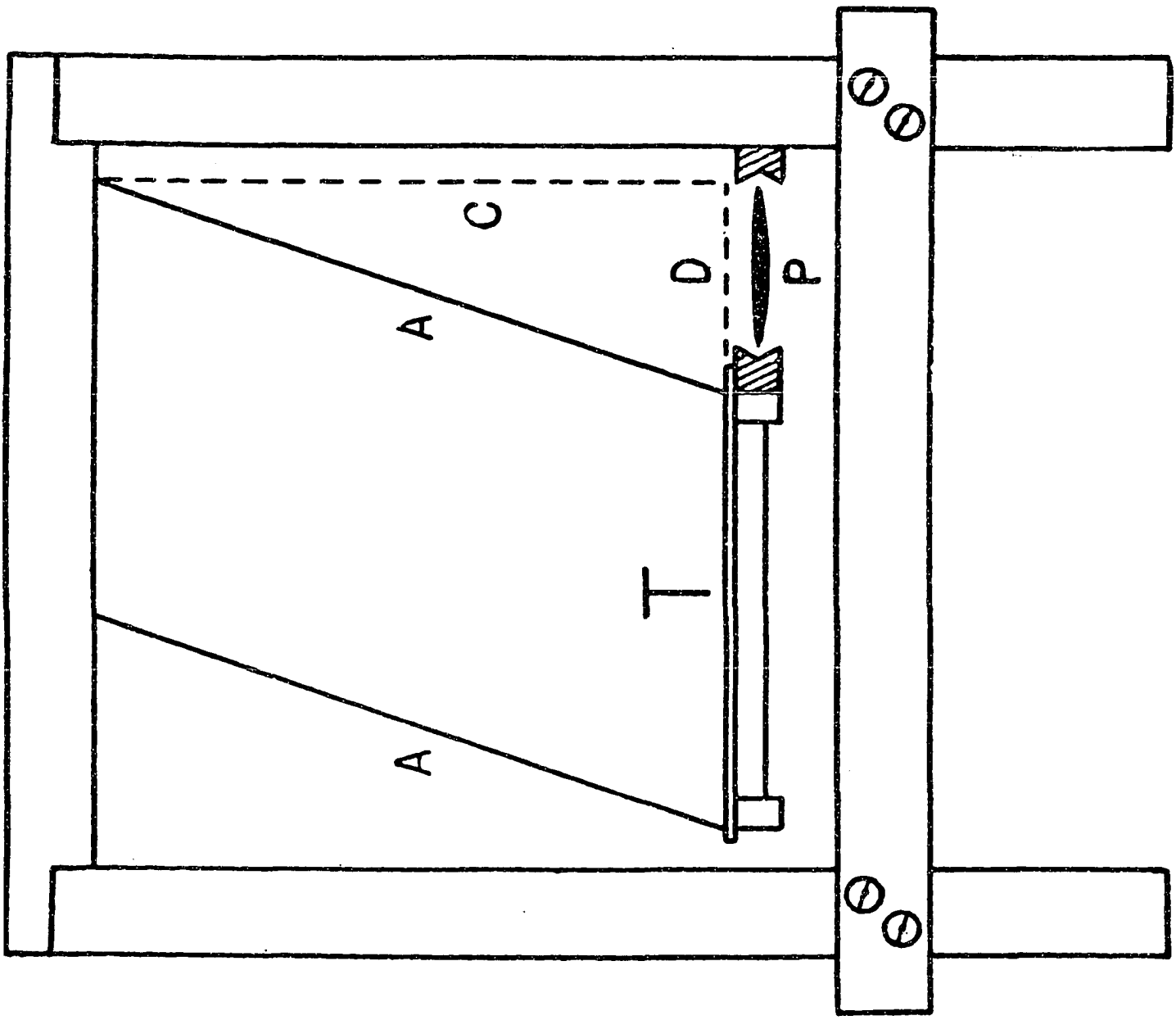
INTRODUCTION

When Yandell Henderson obtained his first records some forty five years ago, he used a plank suspended by wires from a high ceiling (1). "With such a table," he noted, "the heart beat causes not only longitudinal but also lateral movements. The latter have not yet been examined in detail. In fact it is necessary, in order to record the longitudinal movements with accuracy, that the lateral movements should be prevented". How he accomplished this is shown in Figure 1. At each end of the table he placed a sharp-pointed steel pin rested in a case hardened steel cup sunk in the side of the table. The other end rested in a similar cup placed in the post of the frame. As can be seen from the figure, the apparatus was so arranged that the table was slightly off center although this is no doubt exagerated in the drawing.

In the years which followed, records were taken with the subject supine, standing or even tilted, but all of these recorded the head-to-foot displacement alone. These are discussed elsewhere (2). It is only quite recently, however, that interest has begun to develop in other degrees of freedom of the ballistic system. In 1945, Hamilton published a single trace in which the head-to-foot, side-to-side, and front-to-back displacements were recorded simultaneously (3). He has published no records since, and it can be inferred from a careful read-

Figure 1.

Henderson's Table.



ing of his article that this trace was obtained on a temporary instrument constructed to elucidate a single point, i.e. the diastolic waves of the head-to-foot component are related to the standing wave system of the aorta

Hamilton's paper escaped our notice for some time, but shortly after the construction of our first instrument in 1946, we began to speculate as to the magnitude of the remaining translations. Pilot work was accomplished by means of a suitable plank which was placed crossways on the ballistic table. The subject lay on this, first on his back to produce the side-to-side deflection; and then on his side to produce the back-to-front deflection. In this set of experiments although the translations were not simultaneous (timing was accomplished with an electrocardiograph) no distortion was introduced by rotation: and we were able to demonstrate that we were dealing with forces which were by no means of negligible magnitude. Scarborough and his co-workers have since employed the same technique and have published a preliminary report on their work (4).

Design and construction of the two-dimensional ballistocardiograph next followed (2). The front-to-back translation was eliminated as a simultaneous recording with the other two since we could find no way of constructing a three-dimensional instrument without introducing distortion due to rotation. We have found none since. Nevertheless the head-to-foot and back-

to-front displacements can be recorded simultaneously with it if the subject lies on his side.

The mechanical characteristics of this instrument on repeated check in a variety of ways have proved to be satisfactory.

It soon became apparent, however, that the data obtained, excellent though they appeared to be, were difficult to handle. The ballistic form varies considerably from beat to beat, and the analysis of a single complex requires point by point graphical construction from each record. Furthermore a fast paper speed is required if any degree of accuracy is to be anticipated. In this sense, the synthesis suggested an analogy with the monocardiogram of Mann, and Wilson's practical solution employing a cathode ray oscilloscope. Our own solution, which it is the purpose of this thesis to present is similar. Wilson suitably named his record the vectorcardiogram; this we call the vectorballistocardiogram.

THEORY

A rigid cube of iron free to move in space is said to have six degrees of freedom, i.e. six axes of reference are required to describe its possible motion. The cube may be translated in any of three planes, or rotated about any of three axes. A similar cube of gelatin, however, is not a rigid structure and has an infinite number of degrees of freedom. The animal body more nearly approximates the latter; but if the six axes just mentioned could be recorded simultaneously as a ballistocardiogram (see Figure 2) no doubt much valuable information would be obtained, since at the present time only one component is usually recorded (head-to-foot motion).

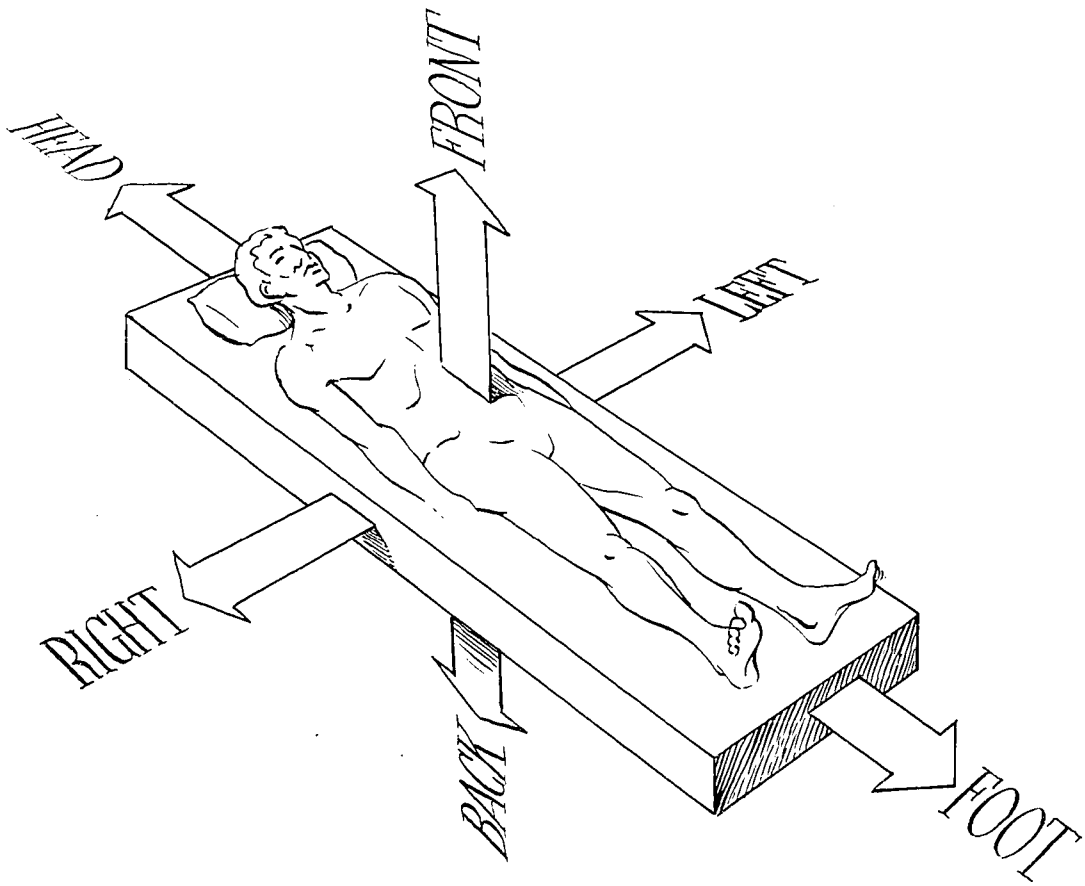
Nickerson in a theoretical discussion considered the body as freely floating in space, and hence without constraint and damping (K = C = 0). In such a condition the ideal deflection becomes

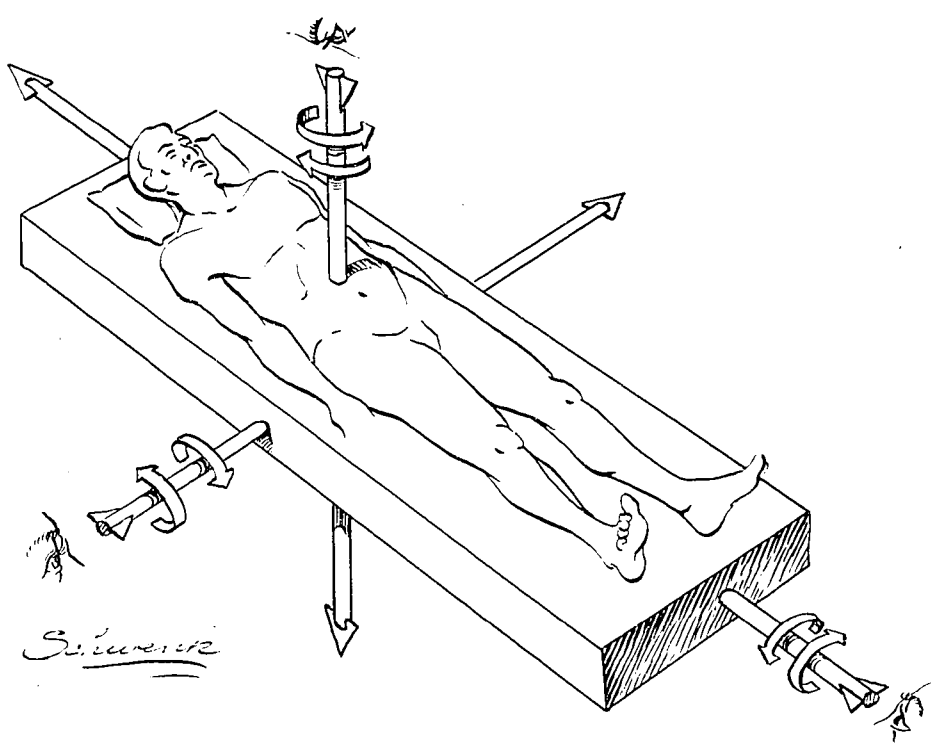
$$x = \frac{-A}{M\omega^2} \sin(\omega t + \delta)$$

Clearly the amplitude of this motion is not constant for a constant amplitude input (since $\omega = 2\pi F$) but depends upon the frequency of the impressed force which in this system varies widely since the fundamental frequency is that of the heart beat. The solution of the problem lies as we have shown in the high frequency ballisto-

Figure 2.

Translations and Rotations.



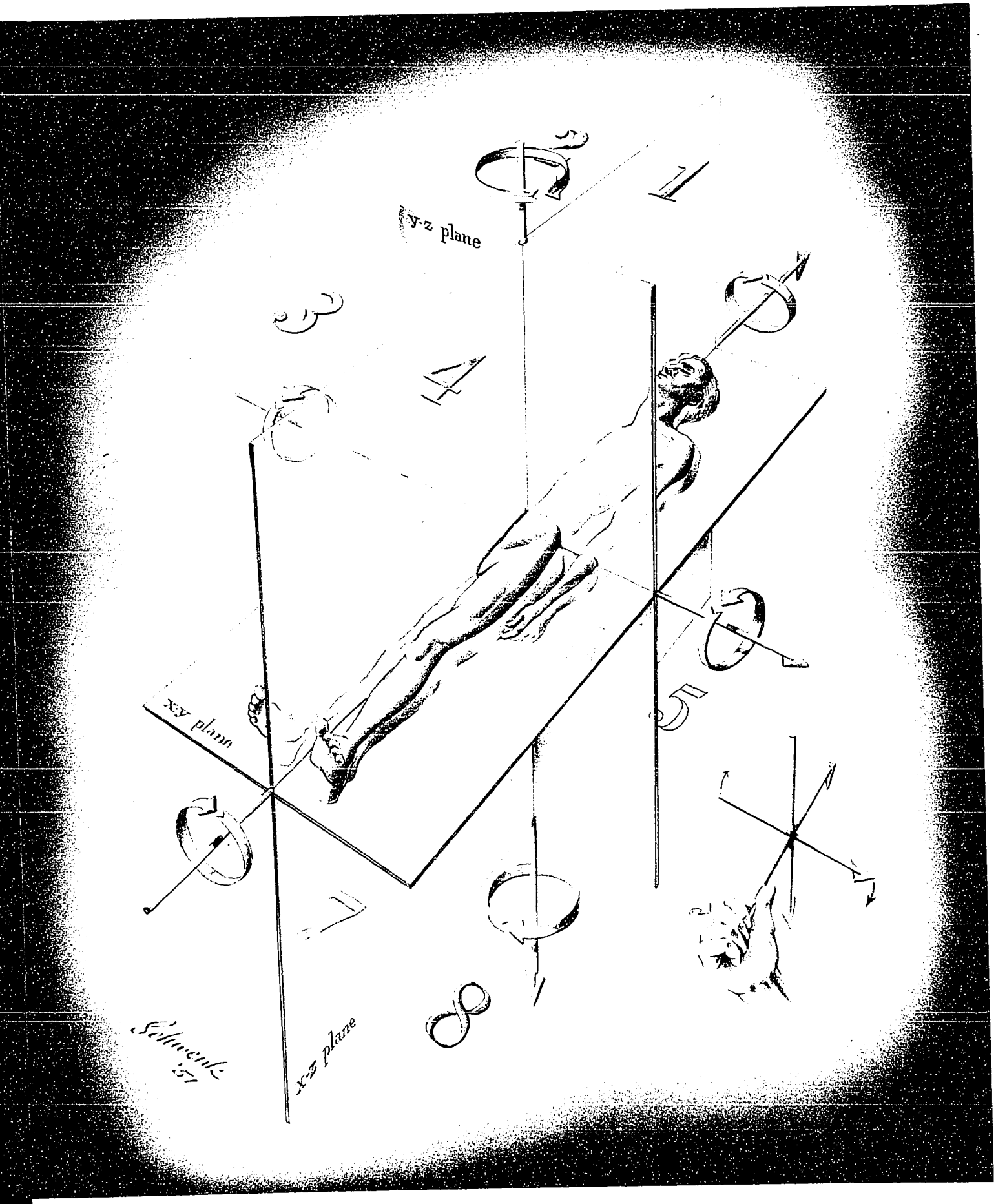


cardiograph (2). In Figure 2 six degrees of freedom for the ballistic bed are diagrammed and arranged in such a way as to constitute a right-handed orthogonal frame. Figure 3 represents a construction which illustrates the planes, rotations, and octants. The purpose of this investigation is to provide a method for recording as accurately as possible the vectorballistocardiogram in the xy and xz planes. It must be admitted that the techniques employed are not strictly comparable: when the subject lies on his side, the coupling between the body and the table are altered, and some shift of the mediastinum undoubtedly occurs. This difference, however, should be a constant one.

Starr and Friedland, in studying the respiratory variation, turned the supine subject on the ballistic bed and were not able to reverse the respiratory variation (5). On this evidence they concluded that the variation was not due to change in the anatomical position of the heart, but was more likely due to the pressure changes within the thorax. They investigated, however, only one rotation and no pressures. With the instrumentation now at hand we are in a position to set up a program for the future in which the vectorballistocardiogram can be recorded simultaneously with pressures in the brachial and pulmonary artery. In the meantime we can investigate the normal and abnormal loops, and explore the physiological changes behind them at a later date.

Figure 3.

Octants.



DESIGN AND CONSTRUCTION

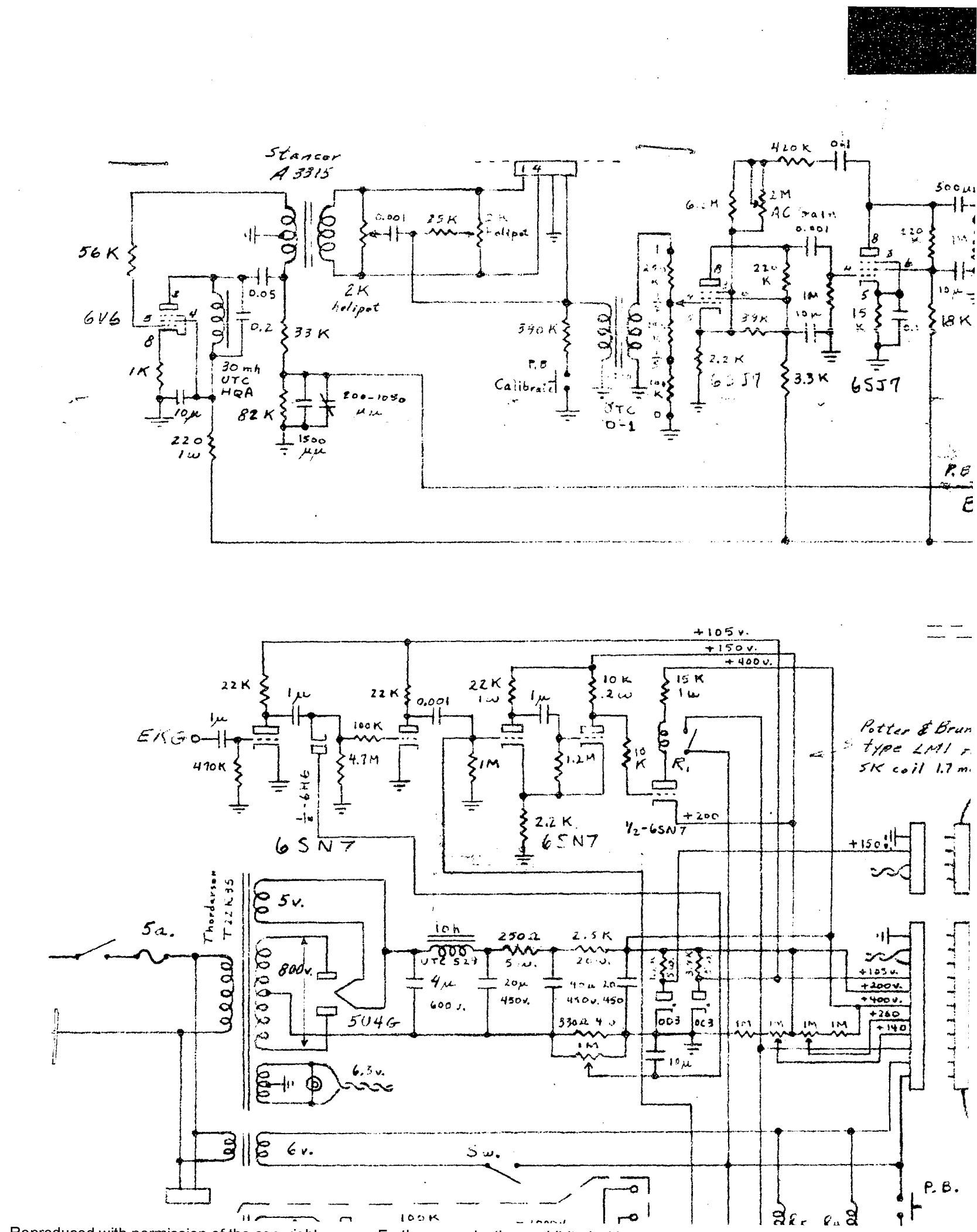
In considering the necessary instrumentation for synthesis of the vector loop, the possibility of utilizing available equipment was first explored. None of the amplifiers on hand, even if modified, was capable of putting out a signal of sufficient strength. Furthermore no available commercial equipment appeared suitable. We then considered the use of the R. C. A. Mechano-transducer tube (which puts out a large signal) in place of the Statham transducer, but abandoned the idea though tempting since this tube is as yet imperfectly worked out and not too reliable for quantitative work.

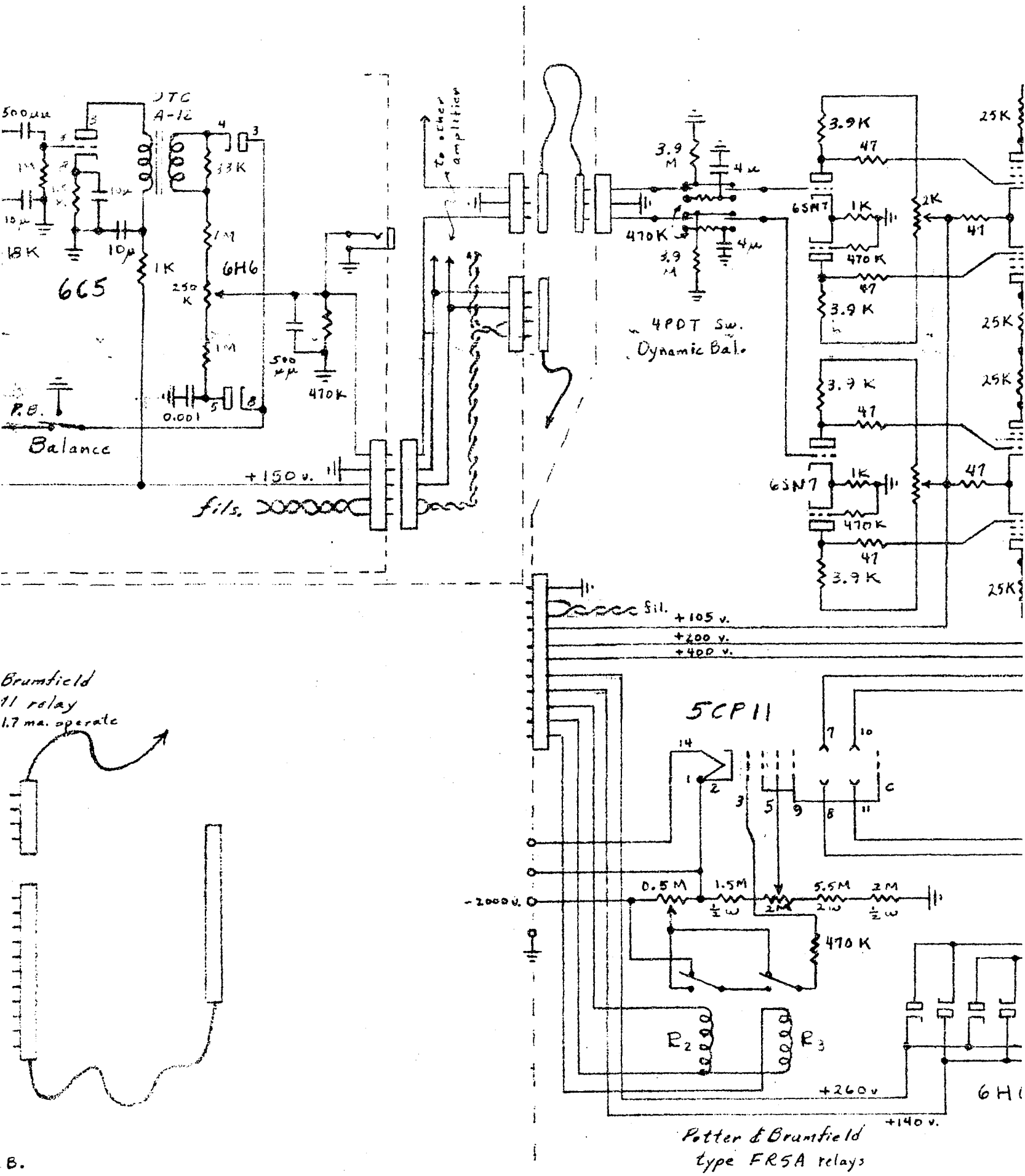
The schematic diagram for the ballistovectorscope is shown in Figure 4. A 2000 c.p.s. oscillator provides the input to the longitudinal strain gauge transducer. This source is used rather than a D. C. supply in order to eliminate the need for a high gain D. C. amplifier with its inherent instability. Means are provided for balancing the strain gauge so no deflection of the table gives zero output.

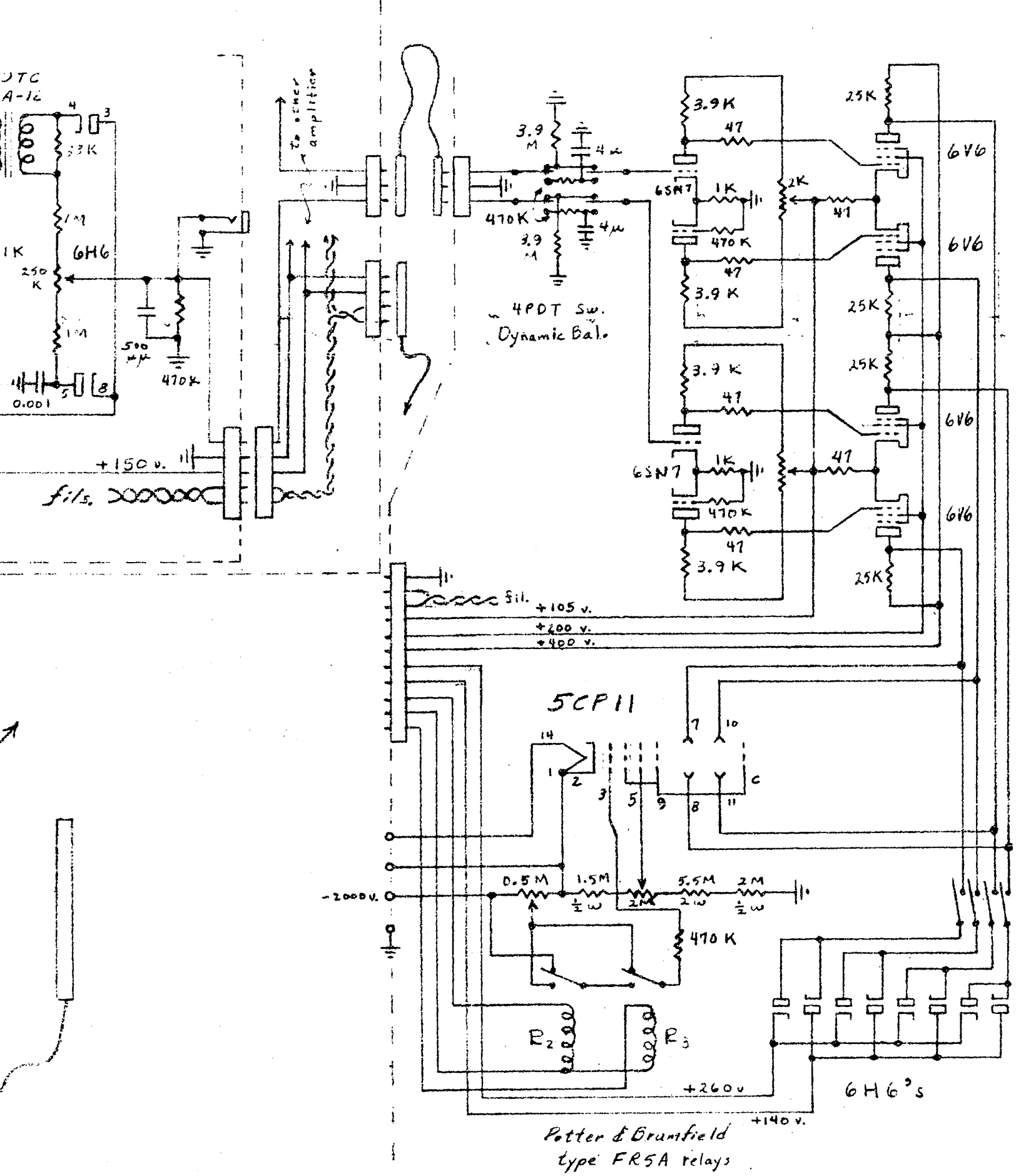
The output of the strain gauge is fed into a phase sensitive A. C. amplifier, demodulated, and then fed to a push-pull D. C. amplifier. The output of this amplifier is then applied to the vertical deflection plates of the oscilloscope tube.

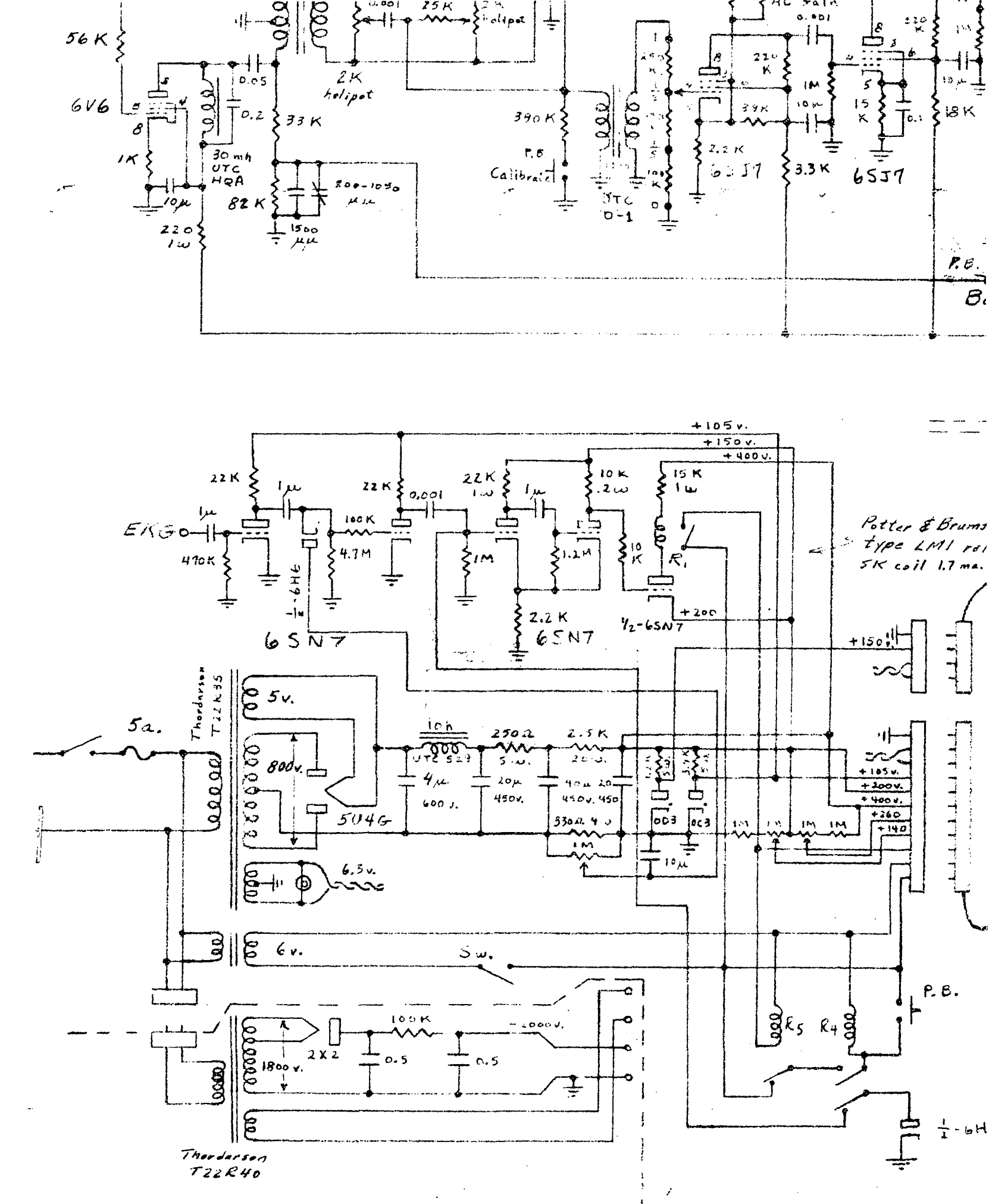
Figure 4.

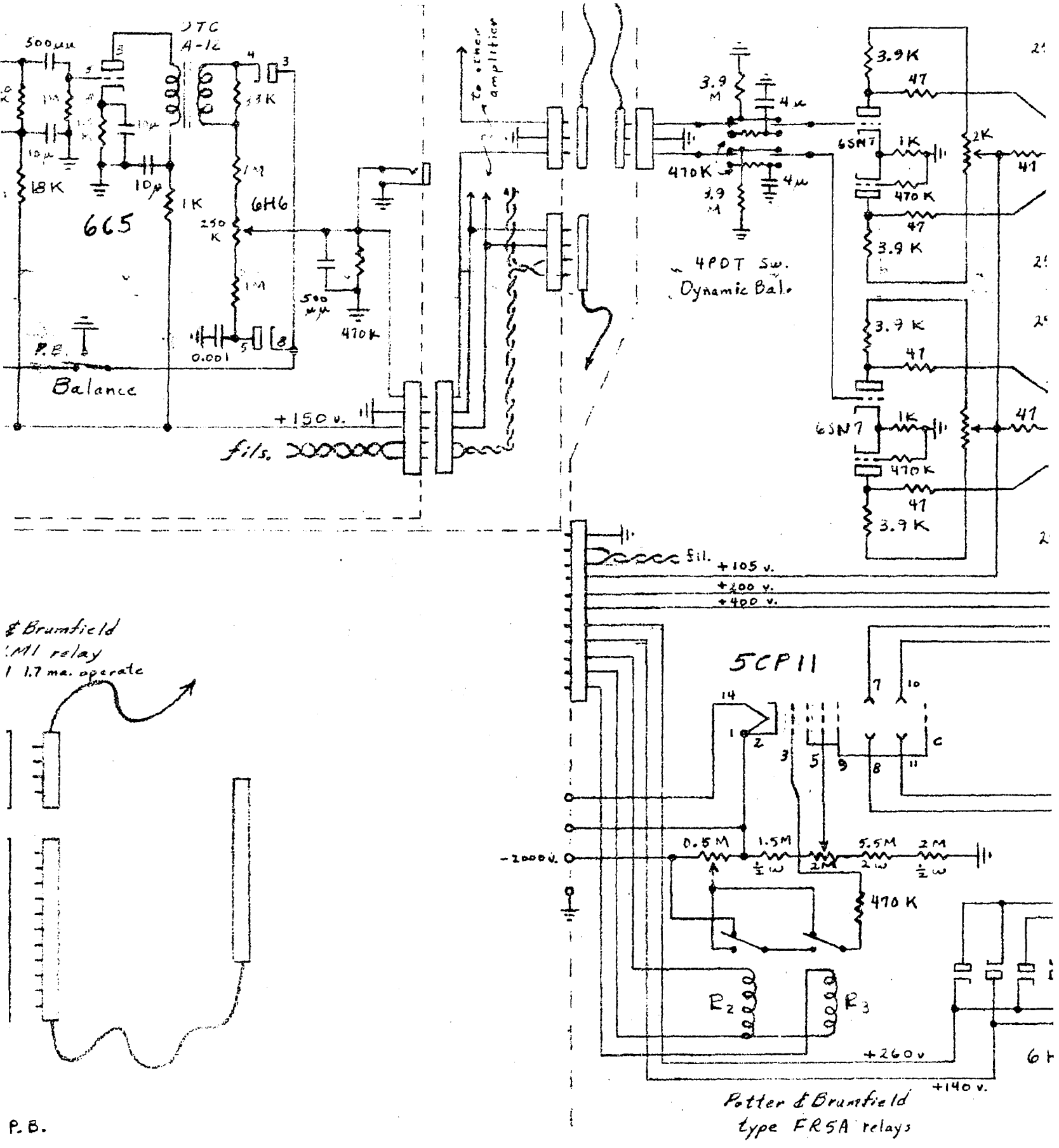
Schematic Diagram.

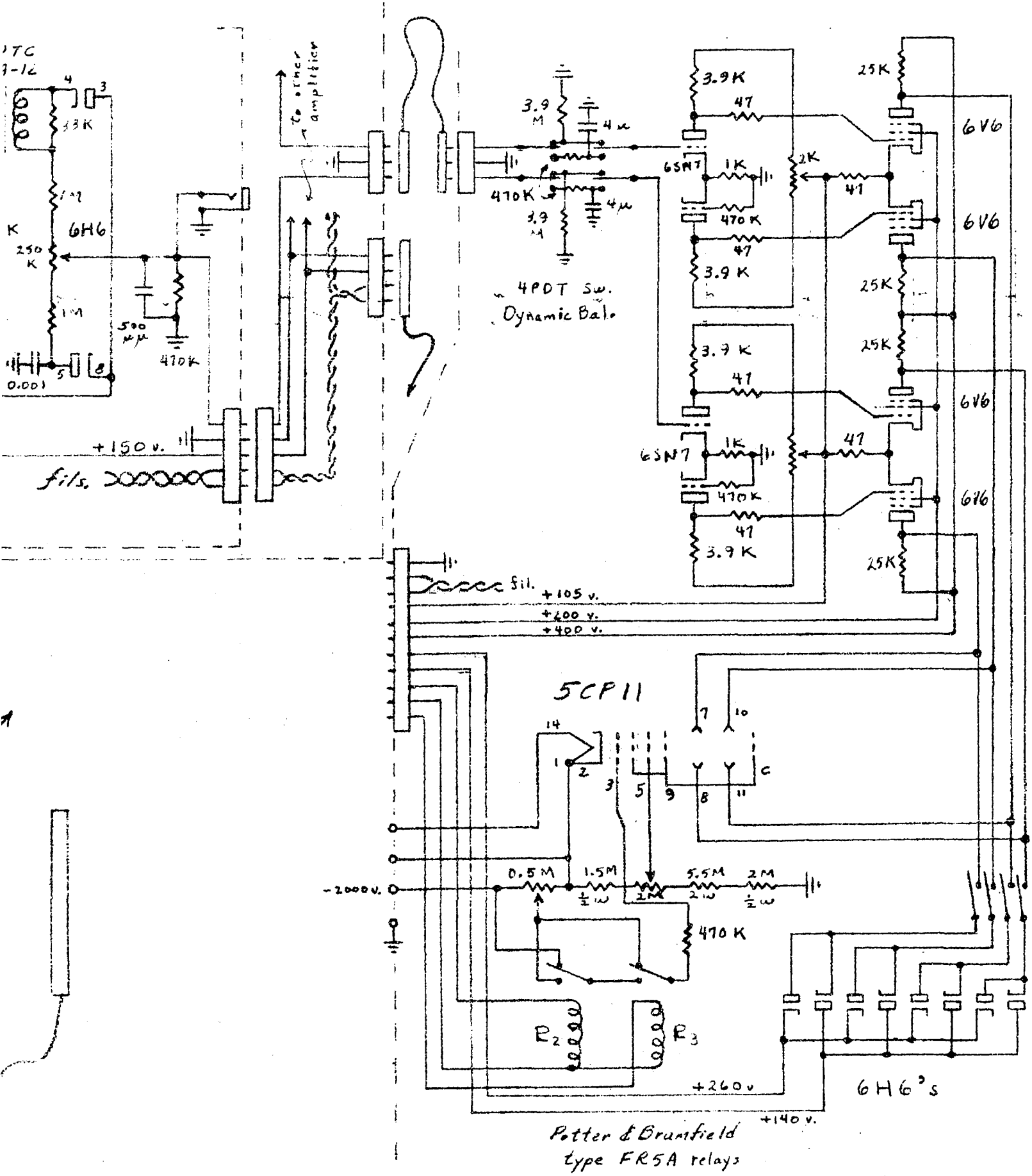












A twin circuit produces the signal from the transverse strain gauge for the horizontal deflection plates.

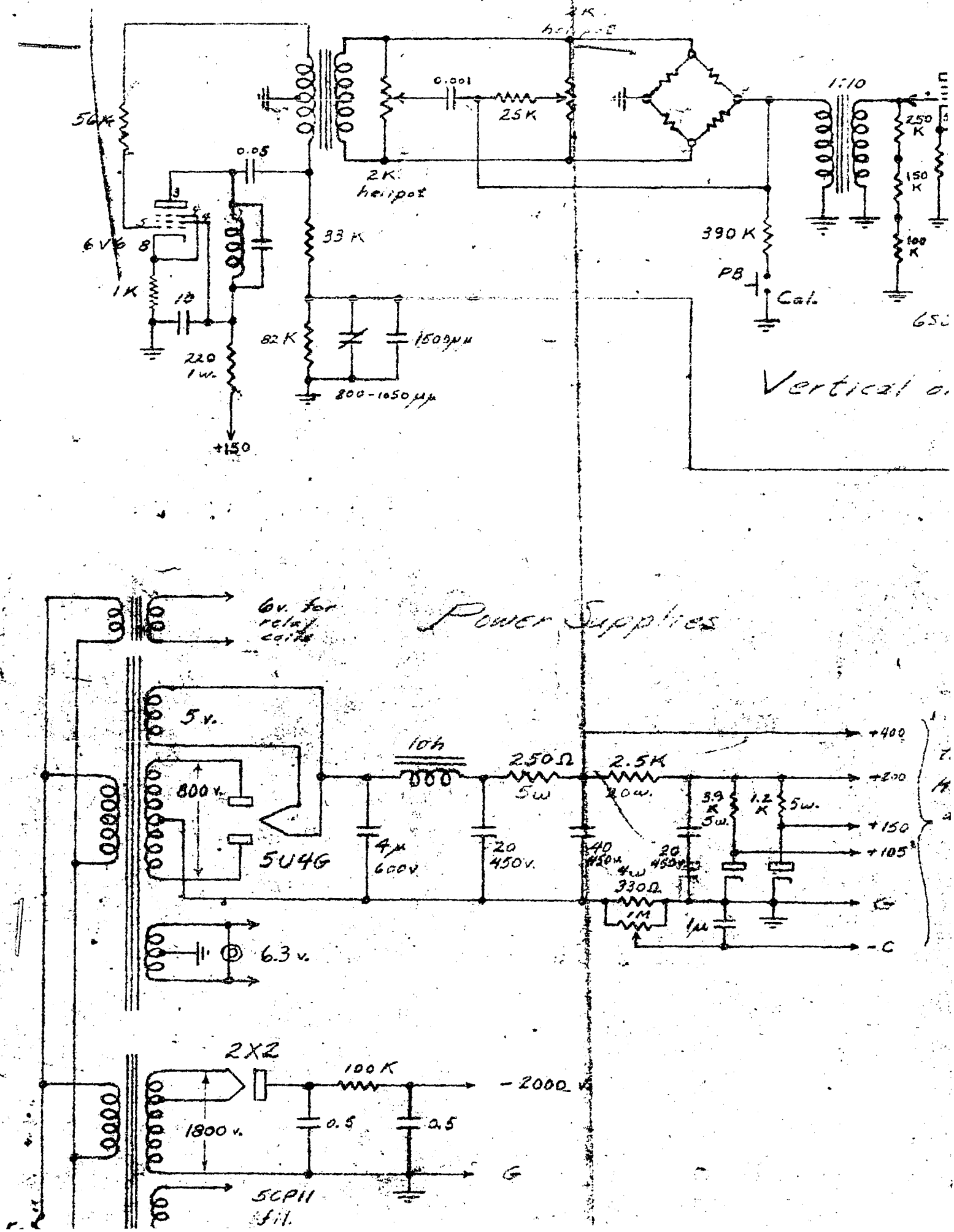
In order to record photographically the pattern for a single heart beat from the face of the oscilloscope, a single cycle circuit was included. A selector switch on the front panel of the scope allows the choice of a single cycle, or continuous operation. With the switch in the single cycle position, the intensity control grid is made negative with respect to the cathode, thus blanking out the oscilloscope beam. The operation of the single cycle push button sets up a circuit to which is fed the output of the electrocardiograph and permits the next r wave from the electrocardiogram to unblank the oscilloscope beam and begin production of the vector pattern. The beam is again cut off either by the next E. K. G. pulse or after a known interval obtained from a multivibrator.

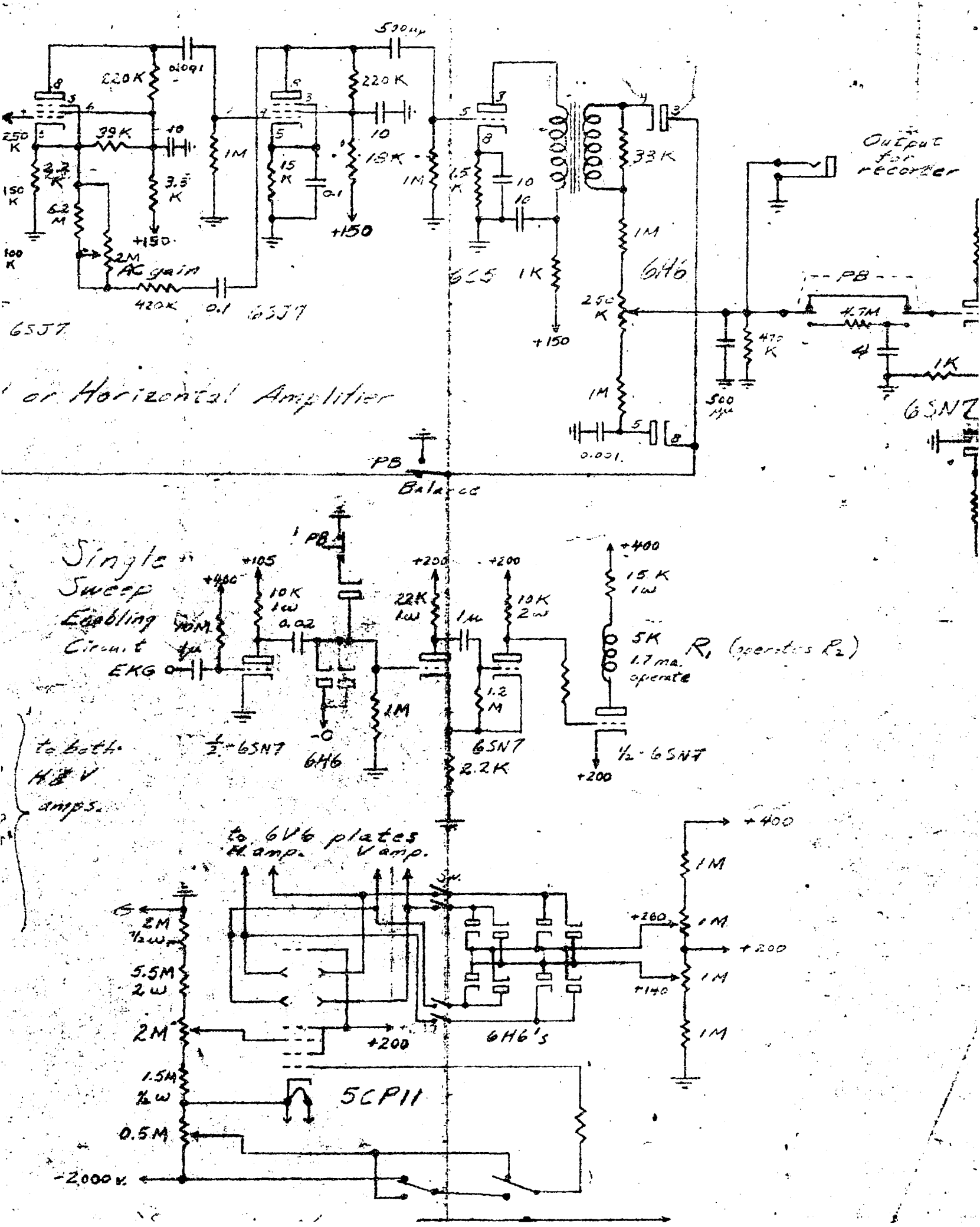
To facilitate balancing, a limiter circuit which limits the beam deflection to approximately 2" is provided. With this in operation it is always possible to see the direction in which the balancing controls must be rotated to give zero deflection.

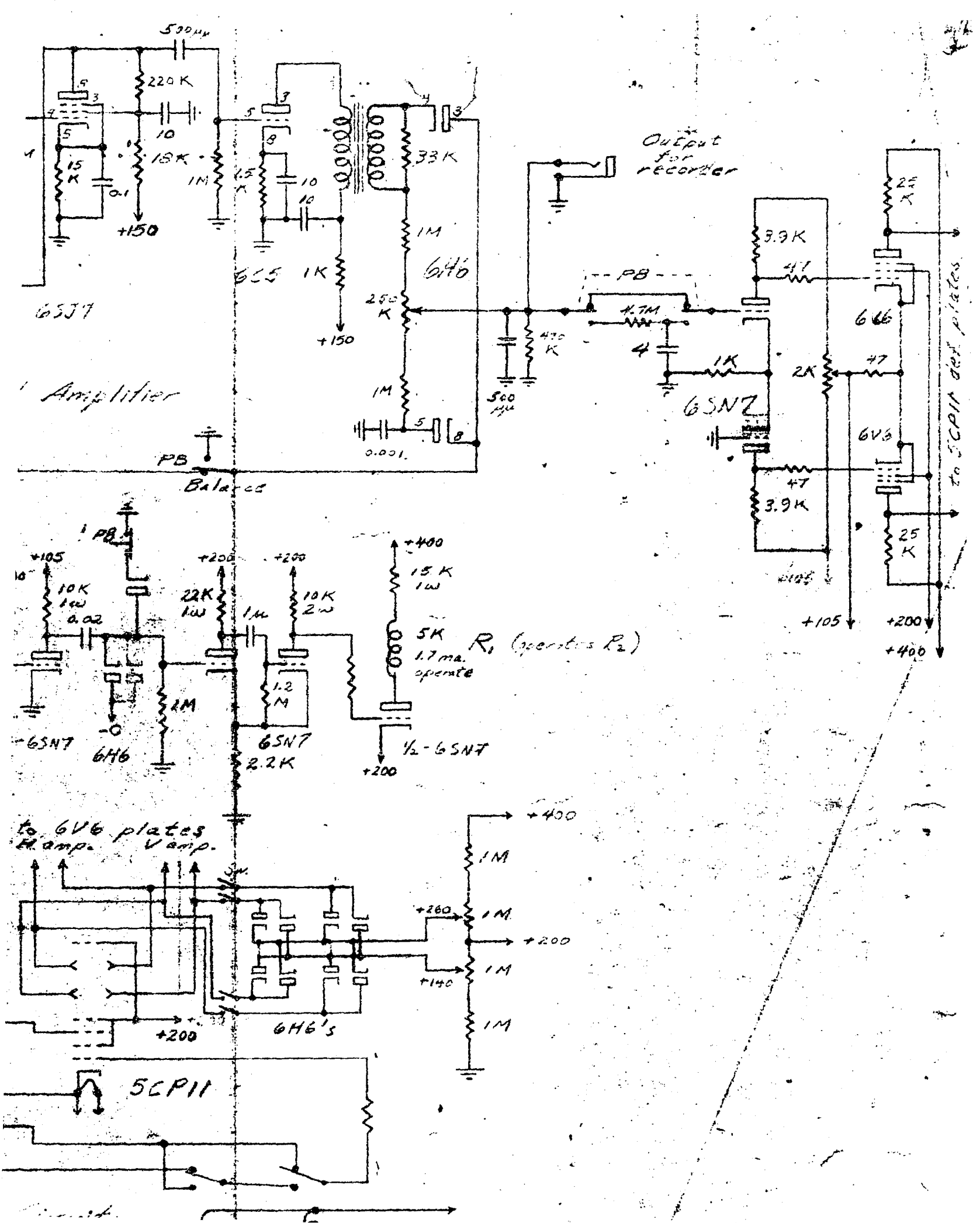
To provide dynamic balancing (that is, balancing of the strain gauge bridge with a subject on the table) a filter circuit may be switched in, which removes the ballistocardiographic signal and allows one to balance the beam to zero on the oscilloscope tube.

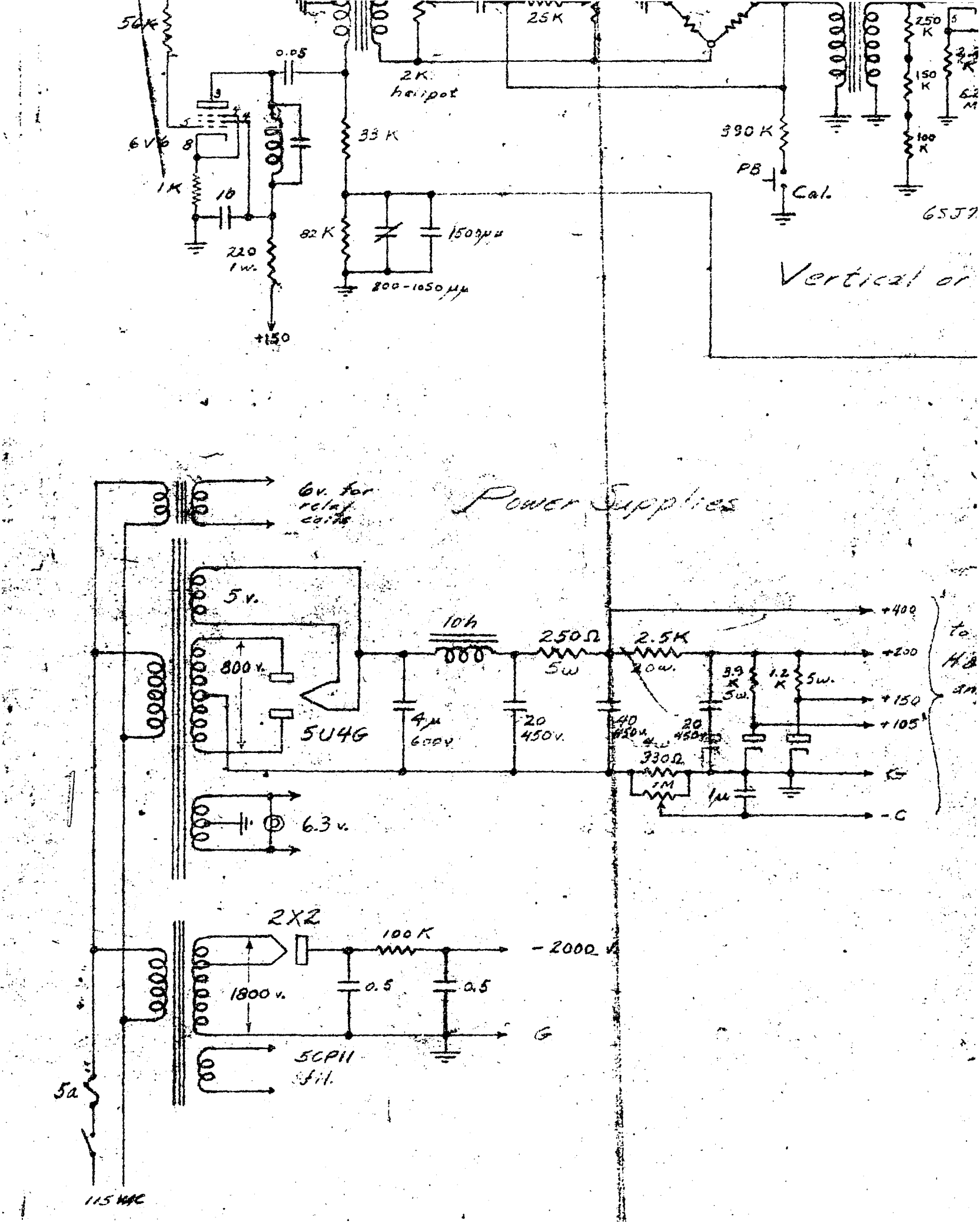
Figure 5.

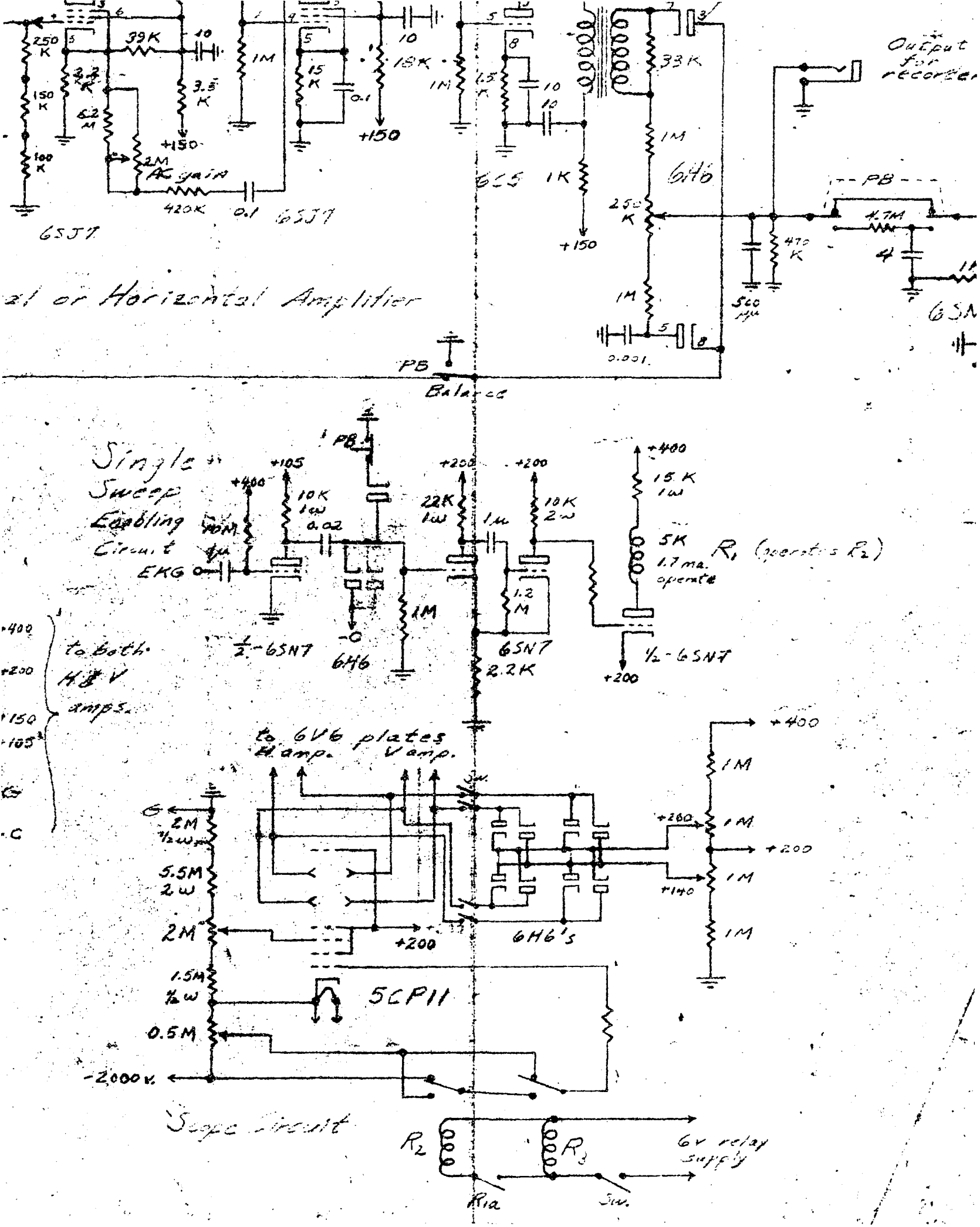
Layout Diagram.











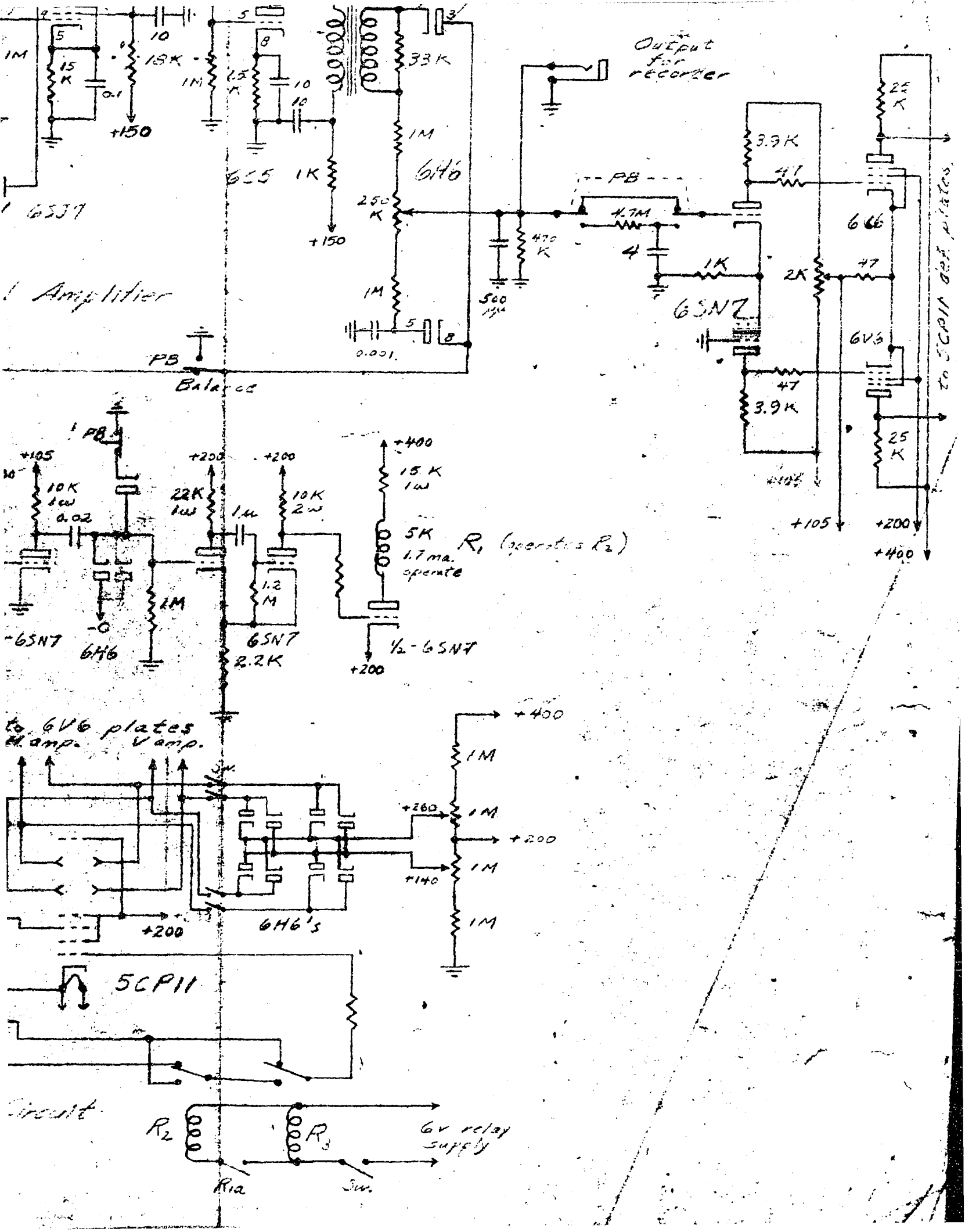
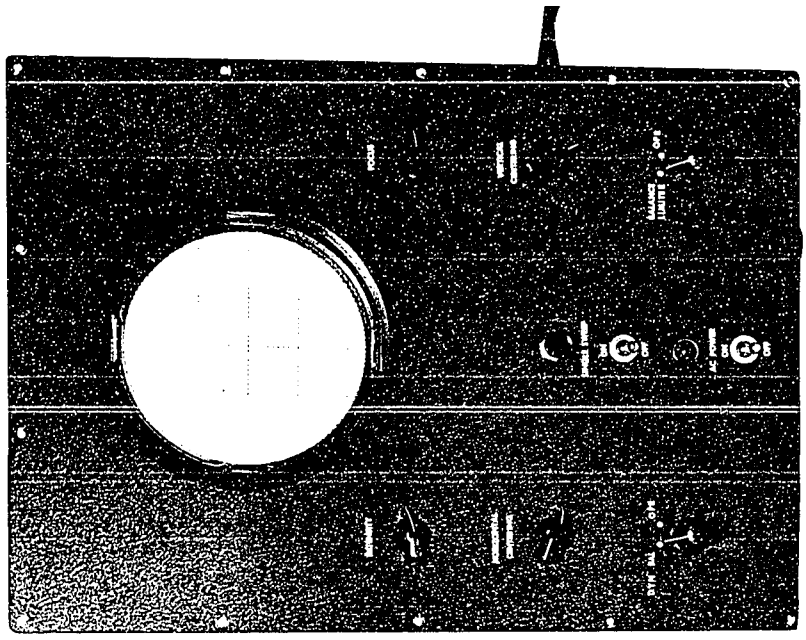


Figure 6.

Front View of One Amplifier and Oscilloscope.



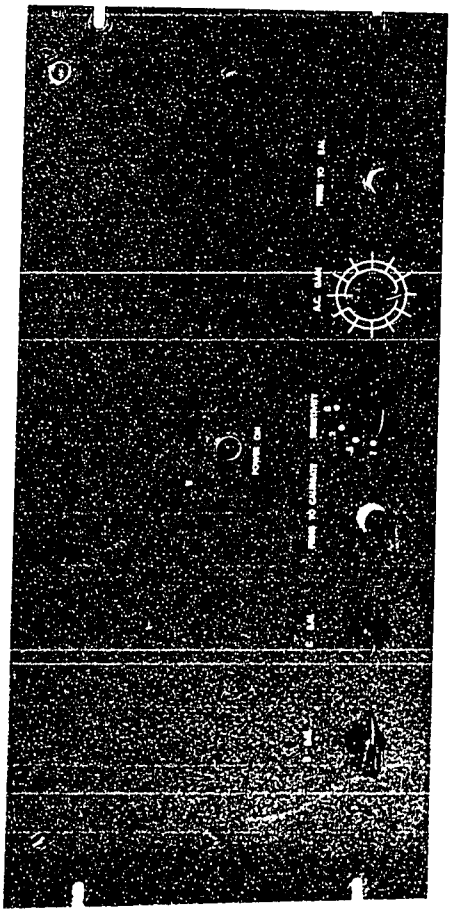
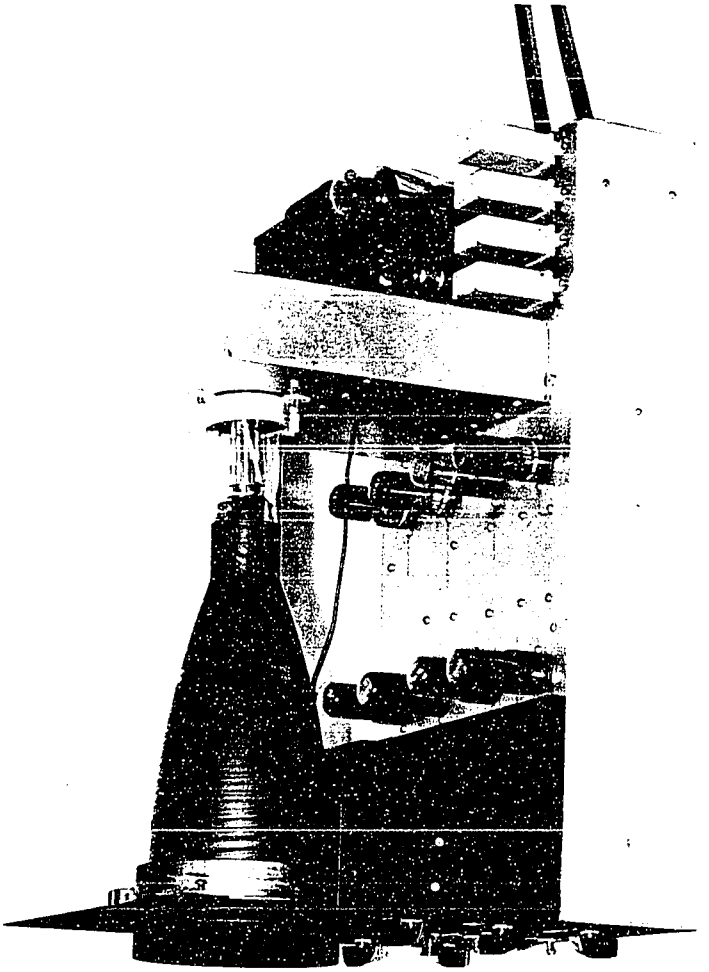


Figure 7.

Oscilloscope and One Amplifier with Covers Removed.



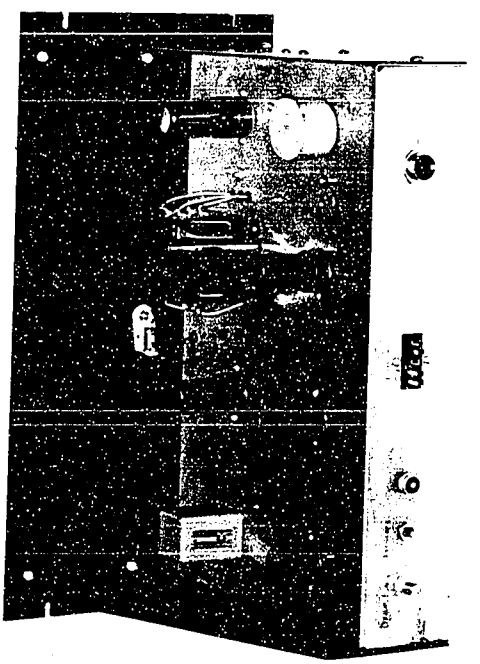
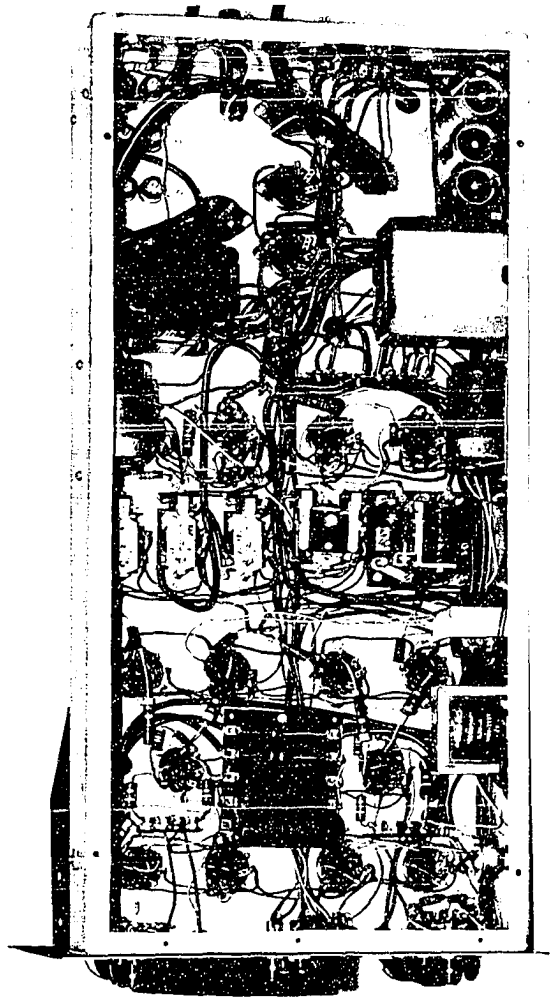
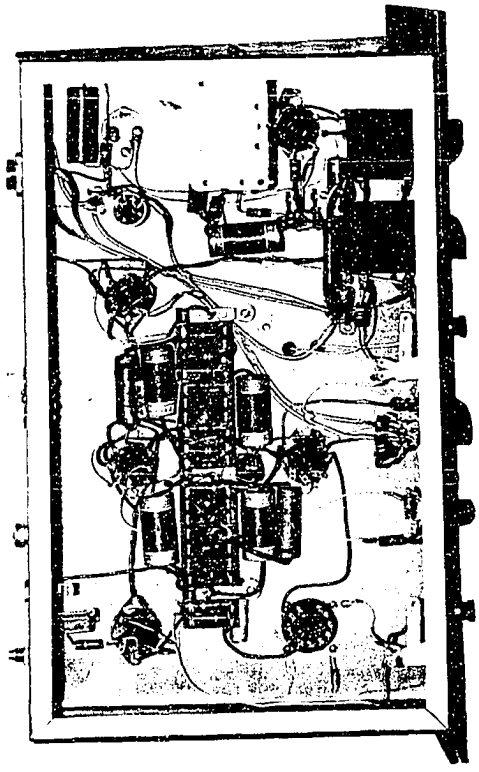


Figure 8.

Bottom View of Oscilloscope and One Amplifier.





RESULTS AND CONCLUSIONS

Figure 9 illustrates the vectorballistocardiogram taken in the xy plane on a 28 years old male (E. O.) in robust health. The upper photograph is taken in inspiration and the lower in expiration. The H wave in both instances is inscribed as a translation headward and to the left, the I wave footward and to the right, and the J wave as headward and to the right. The increased magnitude of the HI and IJ loops during inspiration is apparent as well as the concurrent change of shape.

Figure 10 illustrates a similar vectorballistocardiogram on a 28 years old female (G. H.) with a heart somewhat more vertical than in the preceding subject. Here the same general comments apply except in this case both loops are more nearly vertical as might be expected. Figure 11 represents the vectorballistocardiogram on the same subject taken in the xz plane. Hence it can be seen that the I wave represents a motion which is footward to the right and frontward; and the J wave represents a motion which is headward, to the left and backward.

Figure 12 represents the vectorballistocardiogram in the xy plane on a 22 years old healthy female (M. J. T.) with an intermediate heart. Figure 13 represents the xz translation in the same subject. Here even more marked change with respiration is encountered. Figure 14 illustrates the vectorbal-

Figure 9.

Vectorballistocardiogram in the xy Plane.
upper trace - inspiration
lower trace - expiration

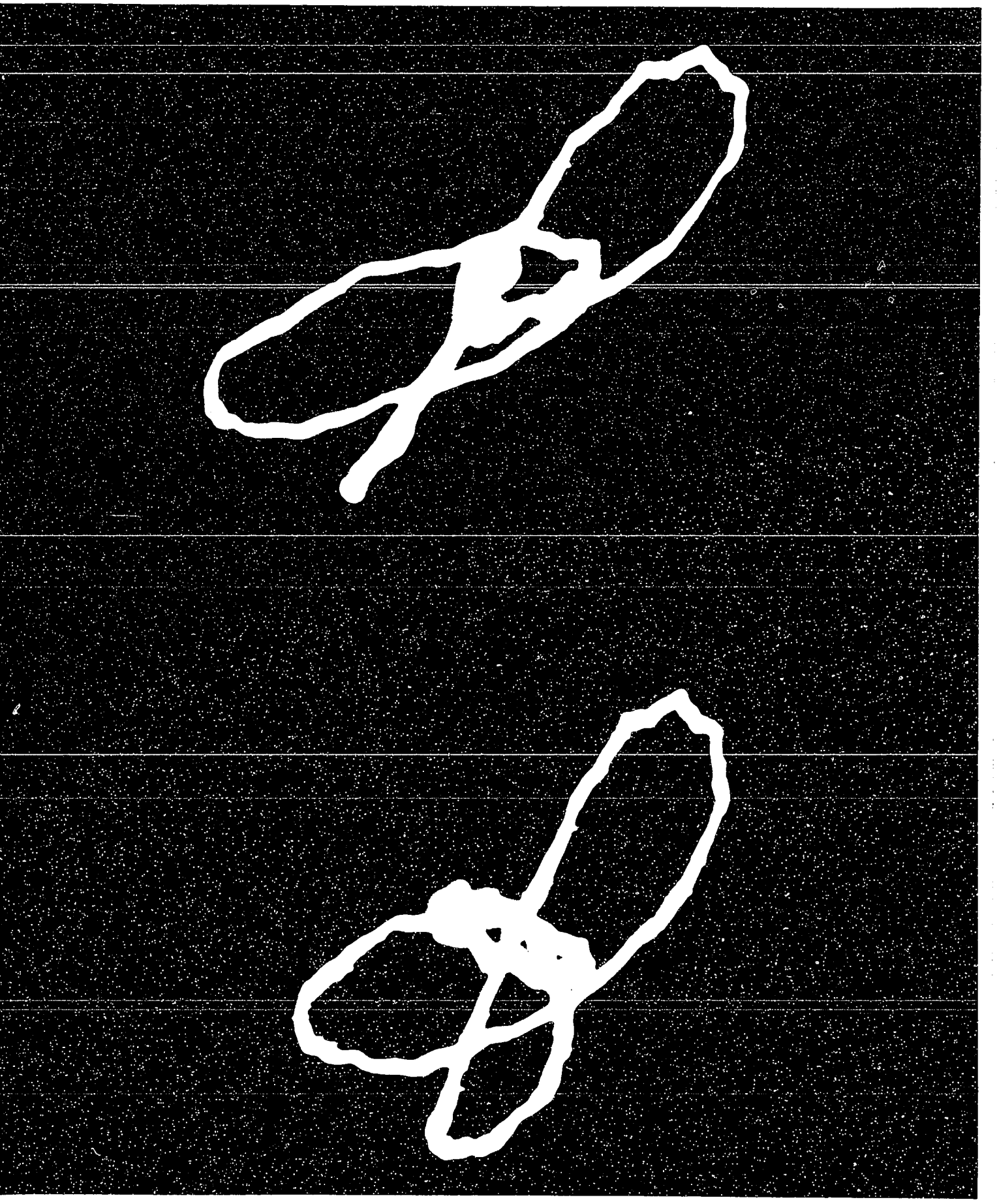


Figure 10.

Normal Vectorballistocardiogram in the xy Plane.
upper trace - inspiration
lower trace - expiration

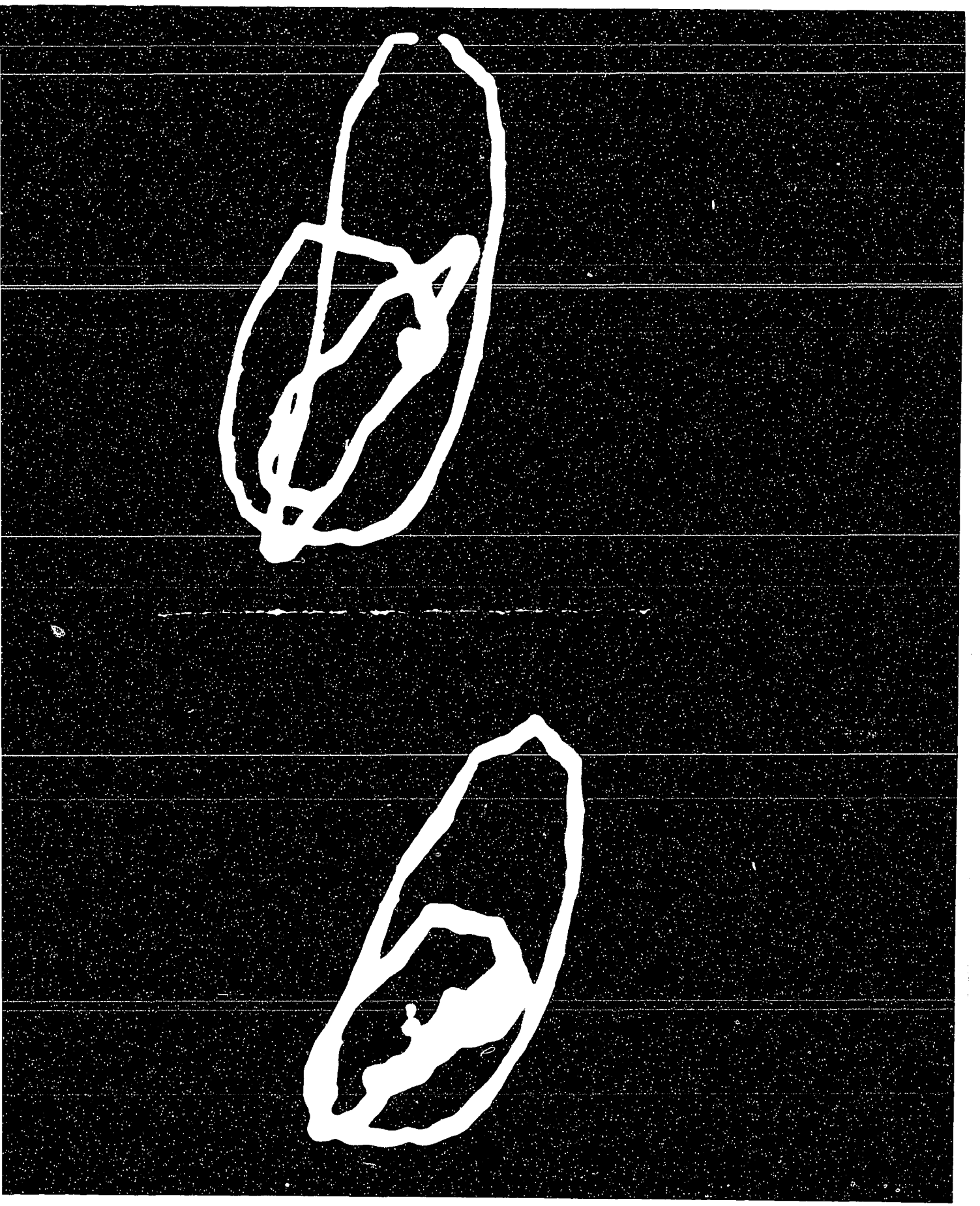


Figure 11.

Normal Vectorballistocardiogram in the xz Plane.
(same subject as in Figure 10)
upper trace - inspiration
lower trace - expiration

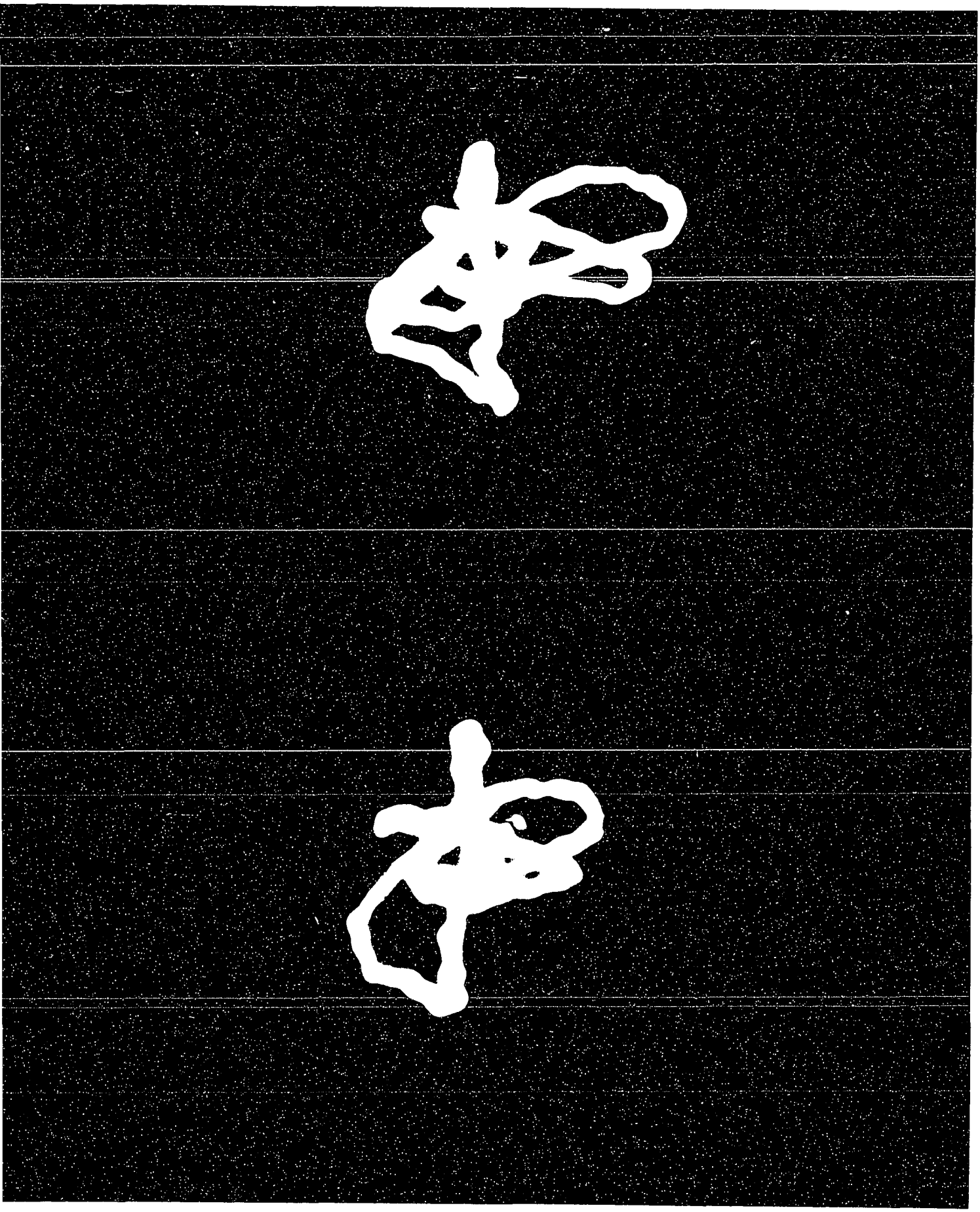


Figure 12.

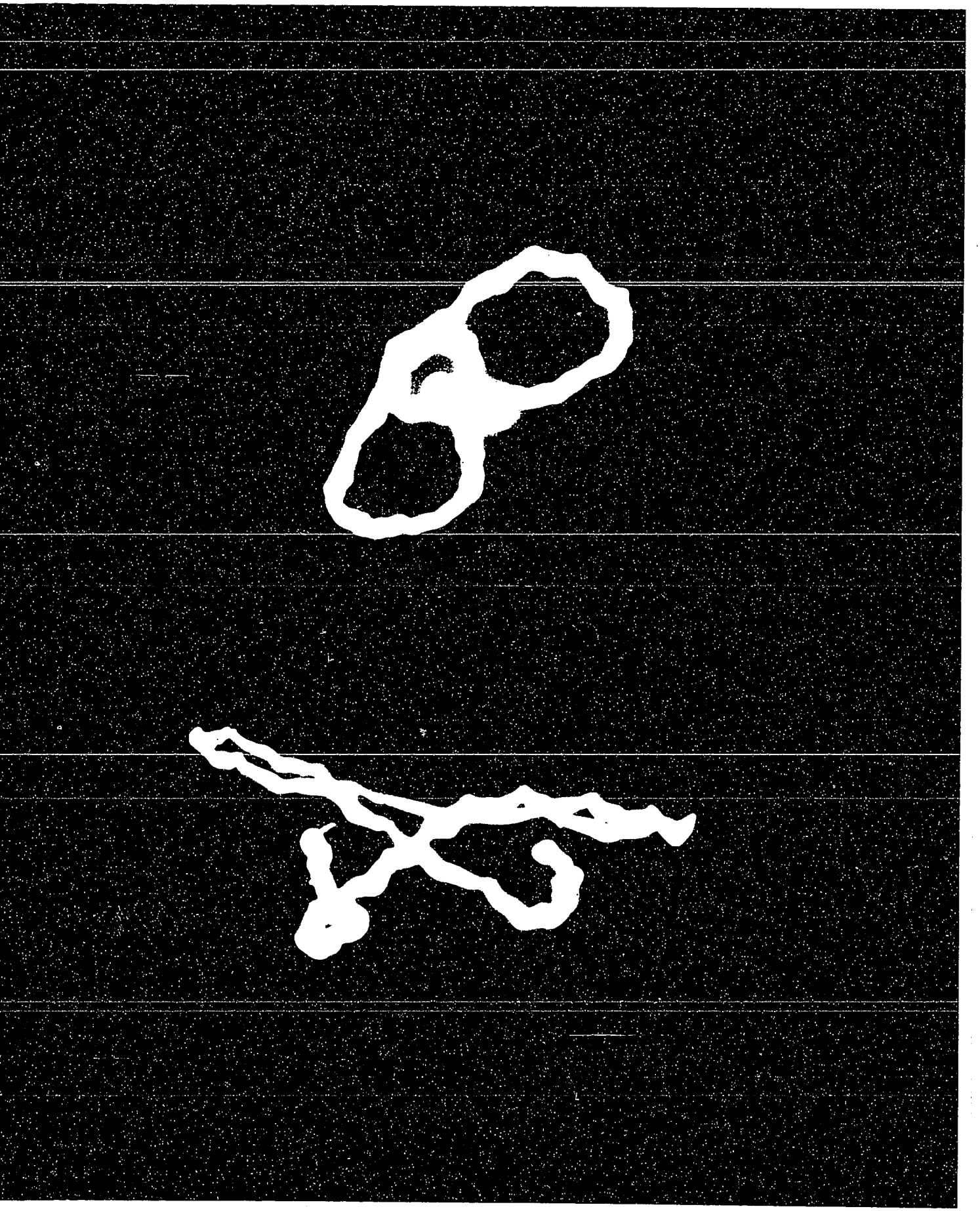
Normal Vectorballistocardiogram in the xy Plane.
upper trace - inspiration
lower trace - expiration

Figure 13.

Normal Vectorballistocardiogram in the xz Plane.
(same subject as in Figure 12.)
upper trace - inspiration
lower trace - expiration

Figure 14.

Horizontal Heart - Essential Hypertension.
upper trace - inspiration
lower trace - expiration



listocardiogram on a 45 years old physician (J. R. B.) with essential hypertension and a horizontal heart. Conspicuous features are the small HI loop and the marked change of direction in the IJ loop with expiration. Figure 15 is a record taken on a 36 years old man with scleroderma (J. S.). Here it is noticed that the loops become larger with expiration, probably an abnormal finding. They also tend to reverse.

Figure 16 illustrates the xy vectorballistocardiogram on a 70 years old man with enlarged and horizontal heart, a normal electrocardiogram, mild pulmonary congestion and a clinical diagnosis of arteriosclerotic heart disease. Here the I wave is represented almost entirely as a rightward deflection. The J loop is wider than it is tall, a finding which we know from previous synthetic studies is never found with a normal heart.

These photographs are representative of the vector loops taken to date. So far it is apparent that the figures recorded on the screen of the oscilloscope vary conspicuously with respiration, and are much altered in disease. The data that we have collected so far also suggests that pressure changes within the thorax as well as the anatomical position of the heart itself are responsible for the configuration produced.

Figure 15.

Scleroderma
upper trace - inspiration
lower trace - expiration

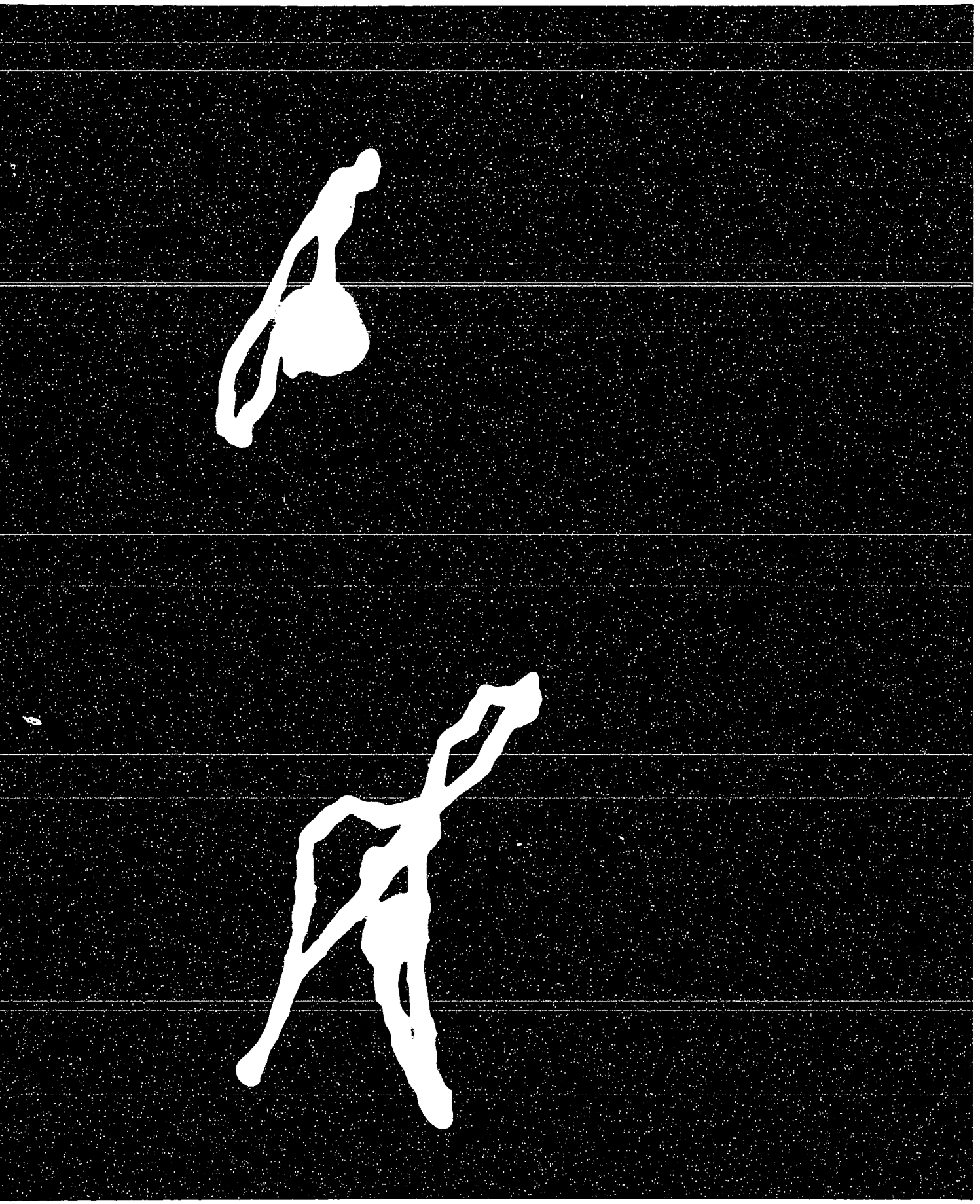
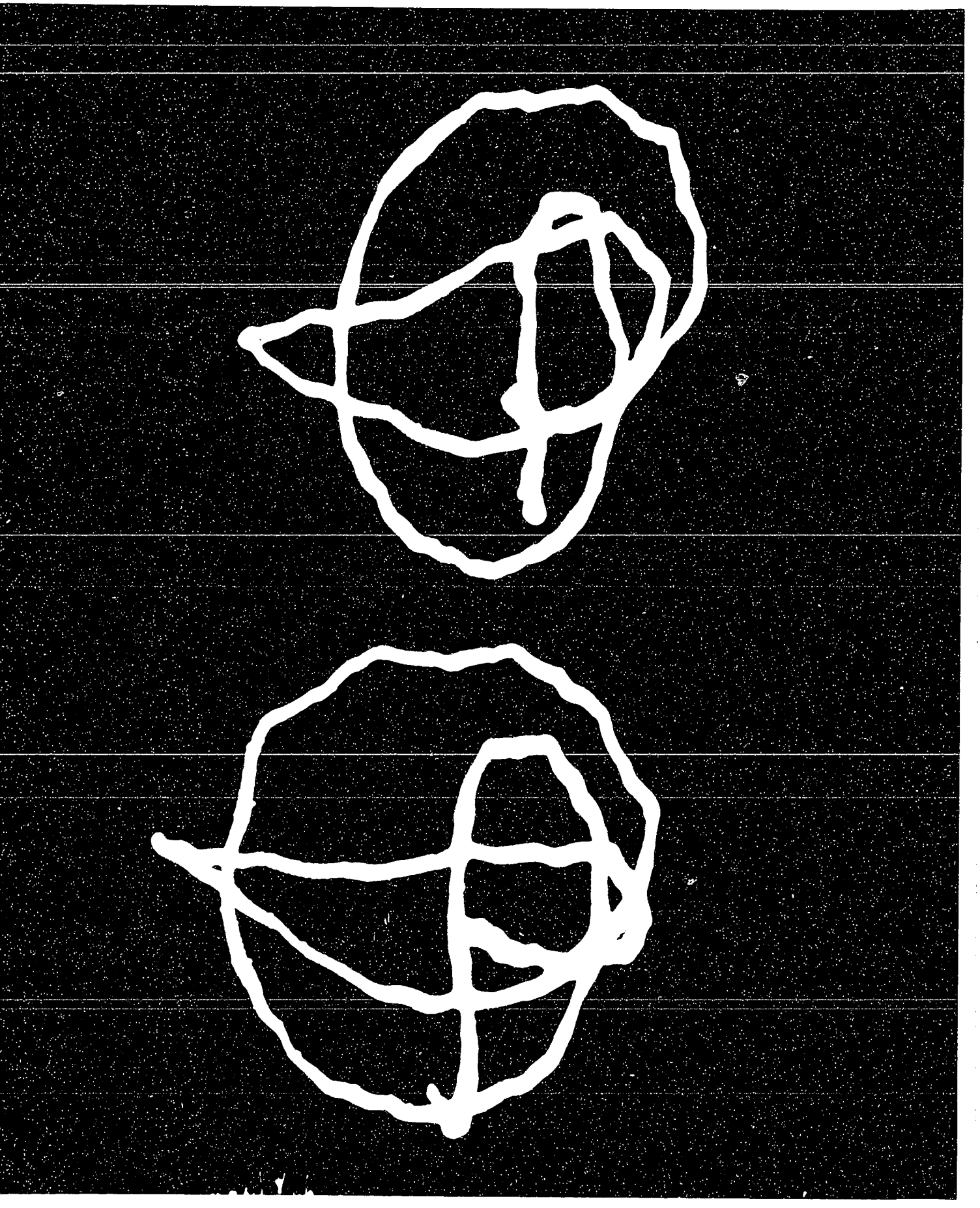


Figure 16.

Coronary Heart Disease.
upper trace - inspiration
lower trace - expiration



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5) Starr, I., and Friedland, C. K., "On the cause of the respiratory variation of the ballistocardiogram, with a note on sinus arrhythmia" J. Clin. Invest., 25, 53, 1946.