The Quantitative Electrokymograph

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The quantitative electrokymograph has been developed in an effort to provide an instrument which will be easier to operate than the electrokymographic equipment currently available. In addition, provision has been made for the recording of both border-motion phenomena and densitometric changes within the heart and great vessels. In the design of the instrument, considerable attention has been directed toward the development of a means whereby electrokymographic tracings may be calibrated. Care has also been exercised in the instrument’s design in order to provide a frequency response that is essentially flat from 0 to 40 cycles per second.

Since its development a few years ago, the electrokymograph has been used by a number of workers to study the border motions of the heart and great vessels. Early investigations have been concerned primarily with an examination of the normal movements of these structures. More recently, however, the study of a number of pathologic states has been undertaken. Characteristic electrokymographic tracings have now been identified in myocardial infarction, constrictive pericarditis, a variety of valvular lesions, and ventricular and aortic aneurysms.

In addition to its use in the study of border motions, the electrokymograph has been applied to a limited extent in the recording of densitometric changes within the heart and lungs. By these densitometric studies, it has been possible to estimate cardiac output and pulmonary arterial pressure with some success.

Although much good work has been done with the electrokymograph, a number of deficiencies within the instrument have seriously limited its application. First, it has not been possible to calibrate the amplitudes of electrokymographic tracings in terms of the physiologic phenomena which have produced them. This applies not only when one has used the instrument to record cardiac and vascular border motions, but also when one has applied the device to study the densitometric changes of a structure. Consequently, most of the work done with the electrokymograph has been qualitative in nature rather than quantitative.

Another defect of current electrokymographic apparatus is the limited frequency response which it provides. At the First Electrokymographic Conference, sponsored and conducted by the National Heart Institute in Bethesda, Maryland in May, 1950, it was reported that many of the electrokymographic instruments which are available to the profession today exhibit frequency responses which extend to an upper limit of only 10 cycles per second. Cardiac and vascular phenomena having a duration less than 0.1 second are therefore recorded with diminished amplitudes and with distorted configurations; furthermore, the tracings do not indicate correctly the exact time at which the phenomena take place. This is well shown in figure 1 where electrokymographic tracings made by rotating a lead sector wheel first in front of an instrument which has a frequency response extending to well over 1,000 cycles per second (curve A) and then in front of an instrument which has a frequency response extending only to 10 cycles per second (curve B) are illustrated. It will be observed that the latter instrument distorts very considerably the square wave pattern produced by the sector wheel. Furthermore, the latter instrument’s tracing lags behind that of the first instrument so that the onset of the tracing incorrectly indicates the onset of the phenomenon which is being recorded by several hundredths of a second. It will be evident from figure 1 that an electrokymograph which has a frequency response that extends only to 10 cycles per second will not give satisfactory recordings of phenomena having a duration...
shorter than 0.1 second; indeed, many of longer duration will be somewhat distorted and delayed.

In addition to the poor high frequency response which has just been cited, present-day electrokymographic equipment also leaves much to be desired in its ability to record low frequency phenomena. Most of the instruments which are currently available respond poorly to frequencies below 0.5 cycles per second and consequently, are not capable of recording reliably any phenomena lasting more than 1 or 2 seconds. Densitometric phenomena which have a duration of 5 to 10 seconds therefore cannot be precisely recorded.

In an effort to overcome the inadequate frequency response and the lack of calibration in present-day electrokymographic equipment, we have developed the instrument which is illustrated in figure 2. Like all electrokymographic apparatus, the device consists of a radiation detector which is attached to the fluoroscopic screen of a roentgenoscope, an amplifier and an oscillograph.

Radiation Detector

The details of the radiation detector are shown schematically in figure 3. The unit consists of a small roentgen grid, a fluorescent screen, and the usual multiplier phototube. The roentgen grid is of a type having a 16 to 1 ratio and is employed in place of the conventional collimating diaphragms of present-day electrokymographs to prevent scattered radiation from the patient under examination from falling upon the fluorescent screen within the radiation detector. We have used a roentgen grid in this application because of its simplicity and small size.

The fluorescent screen, a zinc cadmium sulfide type (Patterson B-2), is mounted on the undersurface of a lucite block which fits snugly against the multiplier phototube. The screen size is approximately 1 cm. wide and 2 cm. long. The lucite block is so shaped that light generated within any portion of the fluorescent screen is diffused evenly over the sensitive surface of the phototube; the sensitivity of the radiation detector is thereby made uniform across its entire surface. This may be seen in figure 4 where the relative response of the electrokymograph, measured by moving a lead slit 1 mm. in width across the sensitive surface of the radiation detector, is recorded. It will be observed that when the slit encroaches upon the sensitive surface of the detector, the response rises to a maximum, remains at this level as the sensitive area is crossed and then falls to zero when the slit passes beyond.

The fluorescent screen and lucite block of the radiation detector (see figure 3) are arranged so that they can be moved a distance of 5 mm. in a direction parallel to the long axis of the phototube or transversely to the incoming x-ray beam. This provision, suggested by Dr. George C. Henny of Philadelphia, has been included to provide a means for calibrating the electrokymograph when one is recording border mo-
tion phenomena. The movement of the screen and lucite block is accomplished by means of a spring-loaded button which extends beyond the end of the radiation detector and which can be pressed by the finger of the operator.

To calibrate the amplitude of a tracing, one presses the button at the end of the radiation detector and observes the amount of deflection produced on the tracing. The movement of the fluorescent screen in the amount of 5 mm. is equivalent to the movement of the structure under examination of a similar amount. At least, this is almost true and indeed would be completely true if it were not for two small discrepancies. One concerns the fact that the motion of cardiac and vascular structures is almost always accompanied by a change in the diameter of these structures; this change contributes to the amplitude of an electrokymographic tracing to some extent. The other is related to the fact that the lung fields are not uniform in density; the movement of the screen therefore may produce some deflection of the electrokymographic tracing beyond that caused by the position of the heart and great vessels. Apparently, however, these discrepancies are small in effect because calculations of cardiac and vascular motions made from electrokymographic tracings are in close agreement with measurements of these motions taken from roentgenographic films exposed in systole and diastole.

The value in millimeters of a recorded border motion is given by the equation,

\[ M = \frac{A}{B} \times 5 \]  

where \( M \) is the border motion of the anatomic structure under examination, \( A \) is the electrokymographic deflection produced by that border motion and \( B \) is the electrokymographic deflection produced by moving the fluorescent screen 5 mm. A typical electrokymographic tracing made from the lower left ventricular border is shown in figure 5. It will be observed that the tracing proceeds in a regular manner until the point \( A \) is reached. At this time, the operator of the instrument pressed the calibration button of the radiation detector and the tracing became displaced upward a distance.
of 9 mm. Beyond point \( A \), the tracing remains at a displaced position until point \( B \) is reached.

In such a case, the tracing would have gradually drifted downward after its first displacement and thereby would have made the calculation of border motion very difficult.

**Linear Amplifier**

A simplified circuit diagram of the amplifier with which the radiation detector operates is shown in figure 6. This amplifier is of a two stage, direct-coupled type which operates a Brush direct-writing oscillograph. The multiplier phototube, \( V_0 \), is coupled to the control grid of the first amplifier tube, \( V_1 \), through the variable resistor, \( R_3 \), a parallel-T condenser-resistor filter and the condenser, \( C_3 \).

The parallel-T filter attenuates sharply the pulsations which occur within the phototube current from the sinusoidal voltage applied to the x-ray tube. Without this filter, these pulsations are sufficiently great to render the electrokymographic tracings completely uninterpretable. For a full-wave rectified fluoroscope, where maximum attenuation is needed at a frequency of 120 cycles per second, the resistors, \( R_1 \), have a value of 2.7 megohms, the resistor, \( R_2 \), a value of 1.35 megohms, the condensers, \( C_1 \), a value of 0.0005 microfarad and the condenser, \( C_2 \), a value of 0.001 microfarad. For a

At this time, the operator released the button of the radiation detector and the tracing returned to its original position. It will be seen that the amplitude of the tracing produced by the motion of the left ventricle is approximately 12 mm. Therefore, according to equation 1, the motion of the left ventricular border in the region where the electrokymographic tracing was taken was equal to \( 12/9 \times 5 \) mm. or approximately 7 mm.

It will be observed in figure 5 that when the calibration button was pressed, the electrokymographic tracing remained displaced until the button was released again. This would not have been so if this type of radiation detector were used on an instrument whose frequency response was poor below 1 cycle per second.
self-rectified or half-wave rectified fluoroscope where the maximum attenuation is desired at 60 cycles per second, the values of the condensers, \( C_1 \) and \( C_2 \), should be double those given.

The remainder of the amplifier is relatively simple. The output of the tube, \( V_1 \), is directly coupled to a pair of 6V6 power tubes, \( V_2 \) and \( V_3 \), which in turn, are cathode coupled to the oscillograph. A 6H6 diode, \( V_4 \), is interposed between \( V_1 \) and \( V_2 \) to linearize the amplifier circuit. With this diode in place, the linearity of the amplifier is essentially uniform over the complete range of voltages needed to operate the oscillograph across its tracing paper. (See figure 7.)

![Figure 7. Response of pen writer in terms of input voltage to the amplifier.](image)

Although the voltages applied to the amplifier tubes are not critical, they should be maintained relatively closely within the indicated values since they have been chosen not only to assure linearity of the amplifier but also to block the amplifier should excessive signals be impressed upon it by the phototube. In this way, harm to the oscillograph by the accidental mishandling of the electrokymograph is avoided.

A. **High Frequency Response.** The presence of the parallel-T filter in the circuit impairs the high frequency response of the electrokymograph to some extent. However, this impairment has been reduced to a minimum by proper design of the filter. The value of the condensers, \( C_1 \), has been made one-half that of the condenser, \( C_2 \), and the value of the resistors, \( R_1 \), has been made double that of the resistor, \( R_2 \). Such values insure peak performance of the filter.\(^4\) Furthermore, the value of the resistor, \( R_3 \), placed across the input of the filter has been made small and the resistance across the output of the filter has been made large relative to the value of the resistors, \( R_1 \). In fact, the resistance across the output of the filter is essentially the grid resistance of the amplifier tube, \( V_1 \), a resistance of the order of \( 10^6 \) megohms. By this design, maximum sharpness and efficiency have been achieved for the filter.

A parallel-T filter, designed in accordance with the foregoing principles and tuned to a frequency of 120 cycles per second, exhibits some attenuation at frequencies as low as 20 cycles per second. A uniform frequency response to 40 cycles per second has been provided, however, in the electrokymograph by the inclusion of an 8 microfarad condenser, \( C_4 \), in parallel with the cathode resistor, \( R_4 \), of the tube, \( V_1 \) (see figure 6). Such a response seems sufficiently high for most electrokymographic work.

B. **Low Frequency Response.** When the radiation detector of an electrokymograph is placed over an anatomic structure and the x-ray beam turned on, the light emitted from the fluorescent screen of the detector consists of a relatively large amount of constant radiation, and a relatively small amount of fluctuating radiation which varies with the movement or density of the anatomic structure under examination. These radiations generate within the phototube large constant and small fluctuating currents respectively. Now it is the fluctuating current which one desires to record and it is necessary to remove the constant current from the electrokymographic amplifier if one is to record the fluctuating current with satisfactory amplitude. In the past, this operation has been accomplished by simple capacitative-resistive coupling between the phototube of the radiation detector and the amplifier. Although this type of coupling has been effective in producing the desired separation of the current components, it has resulted in a poor low frequency response of the electrokymograph. Furthermore, it has complicated considerably the operation of the electrokymograph by producing a great deal of instability of the instrument for 5 to 10 seconds after the x-ray beam is turned on.
The foregoing problems have been overcome in the circuit shown in figure 6 by the condenser, $C_3^*$, and the normally closed switch, $SW$. These components operate in the following manner: When the x-ray beam is turned on, the condenser, $C_3$, charges to the voltage appearing across the input of the parallel-T filter. When the charging is complete, the switch, $SW$, is opened, whereupon the fluctuating potentials generated by the anatomic structure under examination are impressed upon the grid of the amplifier tube, $V_1$. The large constant voltage generated by the continuous light emitted by the fluorescent screen does not reach $V_1$ since it is exactly balanced out by the voltage which has been placed on the condenser, $C_3$. Now if the condenser, $C_3$, is given a value of 0.05 microfarad, it will become completely charged in approximately one second; thus, the electrokymograph is ready to record almost instantly after the fluoroscope is energized. Furthermore, once $C_3$ is charged and the switch, $SW$, is opened, the condenser will remain charged for a long period of time because it may discharge only through the grid impedance of the tube, $V_1$. Since this impedance is of the order of $10^6$ megohms, the condenser will remain charged for many seconds. Indeed, the oscillographic tracing drifts only one division in approximately 10 seconds of electrokymographic operation. Consequently, the low frequency response of the instrument is effectively uniform to frequencies approaching 0 cycles per second.

The condenser, $C_3$, with the aid of the switch, $SW$, performs three important functions: (1) it separates the fluctuating signals which one wishes to record from the constant potentials generated by the multiplier phototube from the continuous light emitted from the fluorescent screen; (2) it improves the low frequency response of the instrument so that this response extends effectively down to 0 cycles per second and (3) it simplifies the operation of the electrokymograph by stabilizing the instrument within one second after the x-ray beam is turned on. This circuit development therefore constitutes a valuable modification of electrokymographic design.

The over-all frequency response of the electrokymograph is shown in figure 8. It will be observed that the response is essentially uniform from 0 cycles per second to approximately 40 cycles per second. Measurements of the phase lag introduced by the attenuated frequency response above 40 cycles indicate that a time delay of approximately 3 milliseconds occurs between the time an event actually transpires and the time it is recorded. Such a lag seems insignificantly short.

**Logarithmic Amplifier**

When one wishes to record border motion phenomena, it is desirable that the electrokymograph have a response which is directly proportional to the intensity of the x-radiation transmitted by the patient. Under this condition, border motion will be recorded with greatest fidelity. When one wishes to record densitometric phenomena, however, a logarithmic response is preferable. The reason for this may be found in the following analysis.

When an anatomic structure changes in thickness or density, the intensity of the x-radiation falling on the electrokymograph varies logarithmically; that is

$$\Delta \log I = B \Delta X$$  \hspace{1cm} (2)

where $\Delta \log I$ is the change in the logarithm of the x-ray intensity falling on the electrokymograph’s radiation detector; $B$ is a constant whose value is governed by the x-ray absorption characteristics and density of the anatomic
structure; and \( \Delta X \) is the change in thickness of the structure. Now, if the electrokymograph has a logarithmic response, the deflection of its oscillograph may be expressed by the equation

\[ \Delta D = K \Delta \log I \]  

(3)

where \( \Delta D \) is the deflection of the electrokymograph produced by the incident x-radiation, \( I \), and \( K \) is a constant, governed by the sensitivity of the instrument. When \( \Delta \log I \) is eliminated from equations 2 and 3

\[ \Delta D = BK \Delta X \]  

(4)

It will be observed from equation 4 that when the electrokymograph has a logarithmic response, the calculation of densitometric values is a simple algebraic procedure.

Because of its usefulness in the study of densitometric phenomena, a logarithmic amplifier has been included in the quantitative electrokymograph. In many respects, this amplifier, illustrated schematically in figure 9, is similar to the linear circuit shown in figure 6. Indeed, the two circuits are essentially identical, from the parallel-T filter to the oscillographic penwriter. The means by which the voltage for the multiplier phototube is provided, however, are quite different in the two instances.

In figure 9, the voltage developed by the transformer, \( T_1 \), the rectifier tubes, \( V_7 \) and \( V_8 \), and the condensers, \( C_5 \), is applied to the multiplier phototube through the vacuum tube, \( V_9 \). Furthermore, the output current of the phototube flows through the resistor, \( R_s \), and the potential developed across it is impressed on the control grid of this tube. With such an arrangement, the intensity of the light incident

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**Figure 9.** Schematic diagram of logarithmic electrokymograph. \( V_n \), 931-A multiplier phototube; \( V_1 \) and \( V_5 \), 6SH7 amplifier tubes; \( V_2 \) and \( V_3 \), 6V6 power tubes; \( V_4 \) and \( V_6 \), 6H6 double diode; \( T_1 \), power transformer; \( R_1 \), 0.27 megohm resistors; \( R_5 \), 0.135 megohm resistor; \( R_4 \), 1,000 ohm resistor; \( R_6 \), 20 megohm resistor; \( R_8 \), 0.35 megohm, 5 watt resistor; \( R_7 \), 0.18 megohm resistor; \( R_9 \), 0.18 megohm variable resistor; \( C_1 \), 0.005 microfarad condensers; \( C_2 \), 0.001 microfarad condenser; \( C_3 \), 0.5 microfarad condenser; \( C_4 \), 16 microfarad condenser.
on the phototube's sensitive surface controls the voltage applied to the phototube's electrodes. Now the sensitivity of a multiplier phototube varies almost logarithmically with the voltage applied to its dynodes. Therefore, the voltage, appearing across the voltage divider, \( R_9 \), \( R_5 \), and \( R_8 \), bears essentially a logarithmic relationship to the intensity of the light falling on the phototube in accordance with equation 3. By means of the diode, \( V_6 \), 1 mm. in the thickness of an anatomic structure will produce a maximum deflection on the electrokymographic paper of 5 mm. Thus, the logarithmic amplifier is a quantitative instrument for densitometric studies.

The circuit illustrated in figure 9 was originally developed by Sweet\(^1\) for photographic densitometry. Its frequency response extends only to an upper limit of approximately 20 cycles per second (curve A, fig. 11). Indeed, with a long cable connecting the amplifier and the radiation detector, the frequency response may not extend even to this level (curve B, fig. 11). However, since the amplifier is used only to record densitometric phenomena which take place over a relatively long period of time, such a response seems more than adequate.

**Discussion and Summary**

The electrokymograph has been constructed so that one may obtain either a linear or logarithmic response by simply throwing a switch on the front panel of the instrument. A single channel electrocardiograph has also been included as a part of the device in order that the time relationships of the electrokymographic tracings may be easily determined within the cardiac cycle.

The operation of the instrument is extremely simple. The switch which operates the oscillograph motor has also been arranged to operate the switch, \( SW \), of figures 6 and 9 by means of

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*Kilovolts peak.

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**Fig. 10.** Response of logarithmic amplifier as a function of the intensity of the roentgen radiation incident upon the radiation detector.

**Fig. 11.** Frequency response of the logarithmic amplifier. (A) Interconnecting cable 10 feet long, 20 \( \mu \)f. per foot. (B) Cable 25 feet long, 20 \( \mu \)f. per foot.
a relay. The physician therefore merely moves
the radiation detector to the anatomic area he
wishes to study and then sets the oscillograph
in motion. Since the electrokymograph stabil-
zizes almost instantly after the x-ray beam has
been turned on, no technicians are needed to
observe when the instrument is ready for re-
cording.

In practice, the quantitative characteristics
of the electrokymograph have proved quite
valuable. The interpretation of many border
motion phenomena have been simplified and
the development of many new technics in the
field of densitometric electrokymography lie
before us. In the latter connection we believe it
is now feasible to differentiate expansile lesions
of the mediastinum from tumors of the non-
expansile type with reasonable certainty.

To date, we have not evaluated the benefits
that may be derived from the improved fre-
quency response of the instrument since we
have been recently interested in studying pro-
cedures for measuring rates of flow, stroke vol-
ume and residual volume of the heart by densi-
tometric methods. There is little reason to
doubt, however, that the improved response
will greatly facilitate the study of many physi-
ologic phenomena.

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