W ILLEM E INTHOVEN

The string galvanometer and the measurement
of the action currents of the heart

Nobel Lecture, December 11, 1925

May I be permitted to communicate something about the string galvano-
meter, its latest improvements and its use in electrocardiography.

The string galvanometer consists of a thin thread conducting the electric
current which is stretched as a string in a magnetic field. The thread, as soon
as the current passes through it, is displaced from its position of equilibrium
in a direction at right angles to the direction of the lines of magnetic force.
The amount of displacement is proportional to the strength of the current
passing through the thread, so that this current can be easily and accurately
measured.

The less the tension in the thread, the weaker are the currents which are
adequate to cause a visible displacement. But, if the current sensitivity is in
this way increased, the string movements are at the same time slowed down,
whilst in most uses of the instrument, one has to deal with rapid variations in
the current. To assess the usefulness of the instrument, we therefore introduce
instead of current sensitivity the concept of normal sensitivity and define this
as the sensitivity at a certain arbitrarily established, constant duration of the
deviation of the string. In more precise form we write

$$G = \frac{u}{T^2\sqrt{A}}$$

in which G is the normal sensitivity and A that strength of current which
causes the deviation u. T is the natural frequency of the freely oscillating
string.

We assume that the movements of the string are damped down and u is
the permanent deviation for a constant current. But T is the frequency which
would be present if the damping down were removed.

In the string galvanometer the normal sensitivity is conditioned by the
magnification $v,$ the field strength $H,$ the mass M of the string and the char-
acteristics of the material of which the string is made, thus

$$G' = \frac{vH}{\sqrt{mwM}} \times \text{constant}$$

The quality of the material is rendered by *mw,* if m = the mass and w the resistance of the string per cm of length. If H is expressed in gauss, m and M in grams, and w in ohms, the constant equals $1/320$.

The normal sensitivity of a string galvanometer can be made 1000 times greater than that of the most sensitive mirror galvanometer.

In order to increase the normal sensitivity one must select a favourable material for the manufacture of the string, use a high magnification and a strong field, and finally reduce the mass M of the string.

The possible improvement of the material soon reaches a limit and this also applies to the increase of the magnification and of the magnetic field used. A suitable electromagnet with a field of about 20,000 gauss can be constructed without special difficulty; it will however hardly be deemed possible to build a galvanometer with a field ten times bigger than this. The cost would be in any event disproportionately high.

If we now consider the mass M of the string and restrict ourselves to strings of a certain constant length, we then see from the formula that the normal sensitivity is inversely proportional to the diameter of the string. We must therefore make the string as thin as possible, only reaching the limit when it is so thin that the observation and reproduction of it are connected with difficulties.

While in many of the instruments in use for the most diverse purposes the string is *2* or 3 μ thick it is however possible to use strings of 0.1 μ diameter and still thinner ones with good results. The figure below (Fig. 1) shows a thin string which was photographed at a magnification of 1800. Its diameter could not be accurately measured. But there were good grounds to estimate this as 0.04 μ, i.e. about 15 times smaller than the wavelength of yellow light and nevertheless it was possible to obtain a photograph which, although it was not rich in contrasts, was still reasonably satisfactory.

A thin string can be induced to move rapidly and under suitable conditions to achieve almost aperiodic displacement, about 0.1 s. Under these conditions the string is strongly stretched and its current sensitivity is only small. For most purposes a greater current sensitivity is needed, so that it is necessary to slacken the string. But then one encounters the difficulty of air-damping which in such a thin string is troublesome and inhibits the movement of the string excessively.

Engineer W. F. Einthoven has therefore made a model in which the string lies in a vacuum and this is specially suitable for the use of very thin strings. We obtained with this model with a string about 2 cm long and 0.1-0.2 μ thick and a magnification of the image of the string of 1800 times, a displacement of 1 mm in 0.01 sec for a current of 10^{-11} A. This corresponds to an unparalleled normal sensitivity and one could think that these conditions would be uncommonly suitable for the study of the small variations of current which play so great a role in physiology and medicine.
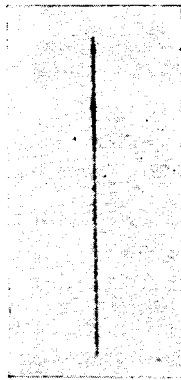
Fig. I. A string the diameter of which is estimated
to be of the order of 0.04 μ.

There is however an insurmountable difficulty. The string does not remain still. Molecular movements due to the temperature cause the whole string to remain in continuous movement. These movements could be named Brownian string vibrations. If one puts the mean energy of a molecule at a certain temperature at $\frac{1}{2}$ m v^2, the string movement which corresponds to one degree of freedom at the same temperature has a mean energy of $\frac{1}{6}$ m v^2. In fact, one obtains about this amount if one calculates the mean energy from the mass of the string and the movement actually observed.

In a high vacuum the string oscillates very regularly with its natural frequency; if a little air enters the movements become irregular. It is self-evident that the air cannot damp down the movements of the string because the movement of the air molecules is itself the cause of the movements of the string. If the string is strongly stretched, its natural frequency is high but the amplitude of the oscillations is small. If one reduces the tension of the string
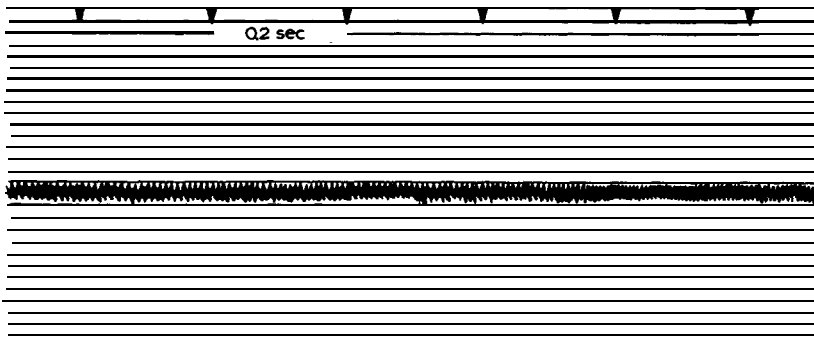
Fig. 2. Brownian string vibrations magnified about 2,000 times. The string is 18 mm long and has a diameter of less than 0.2μ and a resistance of 250,00 ohm. High vacuum. No field-magnet current. The string-circuit is open.

its natural frequency will be lower, but at the same time the amplitude of the oscillations is greater to such an extent that the mean energy of the string's movement remains unchanged.

If the string is in a strong magnetic field and in a closed electrical circuit the usual string movements will be electromagnetically damped down. They induce currents in the circuit outside the galvanometer and must transmit heat there.

Since one might at first sight perhaps think that the Brownian string vibrations had the same result it will appear that here we have a case of <<perpetuum mobile>> of the second kind. Then, if the circuit is closed by an external resistance, this would be warmed even if its temperature were warmer than that of the galvanometer.
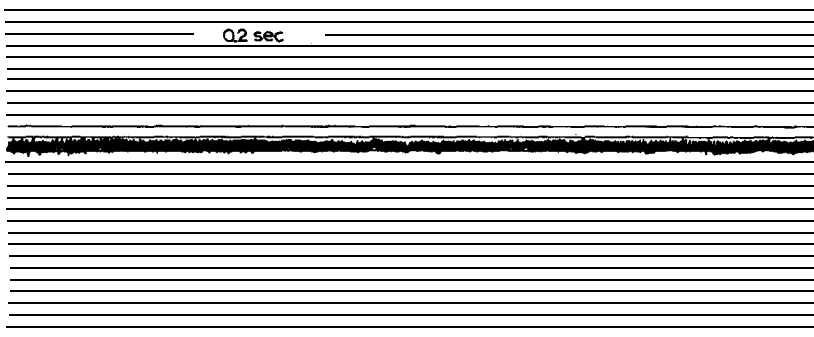

Fig. 3. Air pressure 100μ Hg. Otherwise as in Fig. 2.

The Brownian string vibrations are made irregular by electromagnetic influences, but in fact they experience no trace of damping. The explanation of the phenomenon is found if one takes into account the thermal movements of the electrons in the circuit. These cause Brownian currents which can neither increase nor reduce the Brownian string vibrations.

We thus see that measurement of weak currents with thin strings is in practice limited. But if one has to deal with stronger currents which can cause a sufficiently large displacement of a strongly stretched string, the thinnest string is the best because one reaches with it the greatest normal sensitivity.

The string galvanometer is within the limits mentioned useful for numerous purposes. For wireless telegraphy a model has been built which has rendered very good service as a receiving apparatus. A short string *in vacuo* is tuned to the frequency of the ether oscillations which are sent from some transmitting station. From the ether oscillations high-frequency alternating currents are obtained by one of the usual methods which one sends through the accurately tuned string. As soon as a signal is sent the string is set in motion and its movements are photographed on a moving strip of paper, so that the dots and dashes can be recorded. Thus one has a recording apparatus which is very sensitive, and its decrement can be made precisely controllable and extraordinarily small.

A string 1 mm long can be so stretched that its natural frequency is 300000 cycles per second which corresponds to a wavelength of 1 km. It is difficult to obtain such rapid oscillations of a material in any other way.

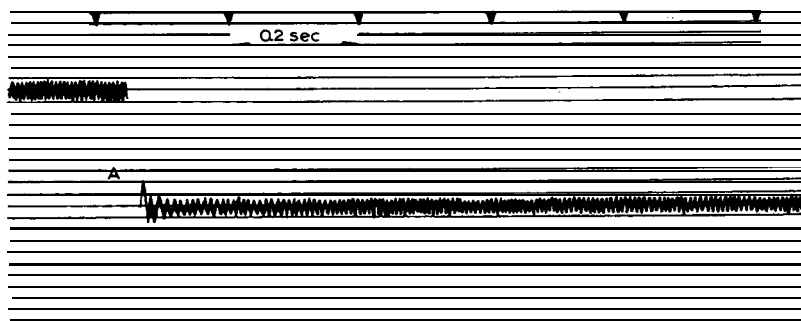Another technical use of the string galvanometer is the recording of sound

Fig. 4. High vacuum as in Fig. 2. The field-magnet current passes through and the galvanometer circuit is closed. At A a constant potential difference is applied to the galvanometer. Otherwise as in the two preceding figures.
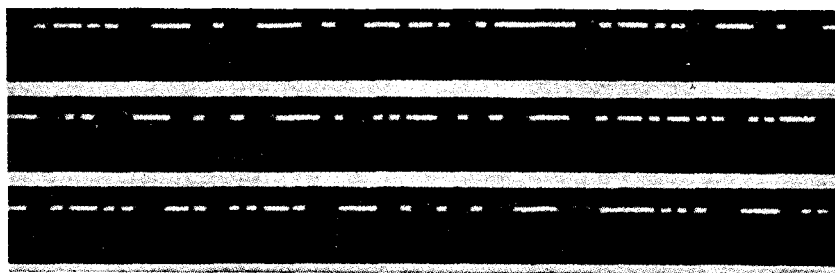
Fig. 5. String-galvanometer recording made in Leiden of wireless signals from Bandoeng, Netherlands Indies. Distance 12,000 km. The string is 6 mm long and is tuned accurately to the incoming waves of $\lambda = 7.5$ km. It thus has a natural frequency of 40,000 whole oscillations per sec. The dots and dashes of the signals are clearly seen in the figure.

waves which can by means of the telephone or microphone set the string in oscillations. One has made full use of the instrument in locating the source of the sound.

In physiology the string galvanometer has been used with success for recording muscle, nerve and skin currents and also those of sense organs.

We mention also the psychogalvanic reflex phenomenon, the heart sounds and the action currents of the heart, and must discuss the latter in further detail.

Just as each muscle when it contracts generates an electric current, so the heart develops electricity at each systole. This was first described by Kölliker and Müller. The English physiologist Augustus D. Waller then showedthat the differences in potential which arise in the heart are transmitted to various parts of the body and that with a sensitive measuring instrument, the capillary electrometer, variations in potential in the human heart can be observed. One needs only lead the current from the hands and feet to. the measuring instrument in order to see the variations of the current which show the same rhythm as that shown by the heart's action.

Fig. 6. Reception of wireless signals from an arc transmitter with two galvanometers. The string of one is tuned to the working wavelength and that of the other to the wavelength used when not transmitting signals. Whilst one string oscillates the other remains quiescent and vice versa.
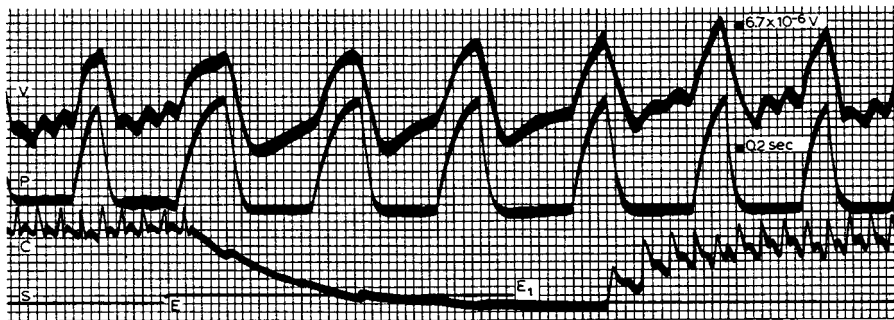
Fig. 7. Vagus currents of the dog. Recording of the currents from the peripheral stump of the left N. vagus. *V,* vagus currents; *P,* pneumogram of the own respiratory movements of the animal; C, blood-pressure curve; *S,* signal. Between *E* and *E,* the peripheral stump of the right vagus nerve was stimulatedby induction currents. The heart became arrested. The heart waves disappear in the left electrovagogram, whilst the respiratory waves persist.

If one records the displacements in the measuring instrument, one obtains a curve called the electrocardiogram (ECG). But because of the imperfections of the capillary electrometer the directly recorded curve does not give an accurate picture of the actual variations in the potential. In order to obtain a fairly accurate picture one must construct a new curve based upon the properties of the instrument used and the data of the recorded curve and this takes much time. This stood in the way of the practical use of electrocardiography for the investigation of heart diseases, and general interest in the ECG only developed later, after the string galvanometer had made it possible to record easily and quickly the required shape with satisfactory accuracy.

There was a certain satisfaction in learning that the picture constructed by means of the time-consuming measurements and calculations from the data of a capillary-electrometer curve corresponded in shape and measurements
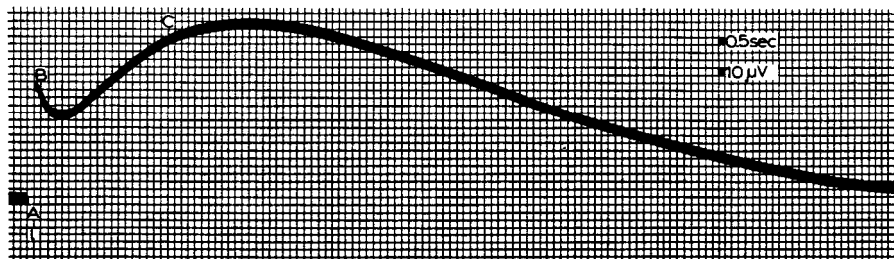

Fig. S. Retinal currents. Combined reaction of the three substances *A, B,* and *C.* Eyes in darkness. At *l* instantaneous illumination with strong light for 0.01 sec.
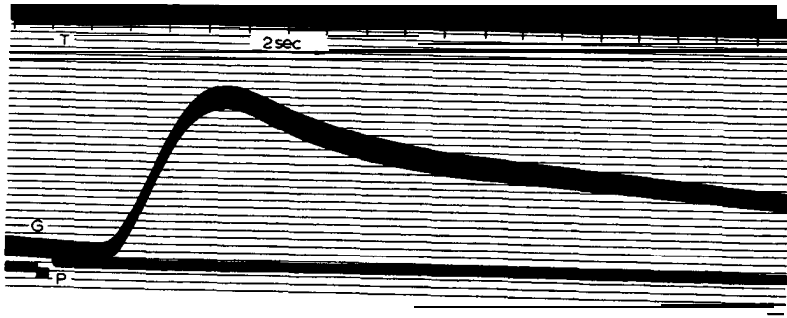
Fig. g. Psychogalvanic reflex phenomenon. Current lead from the thumbs and fingers of a hand. At *P* acoustic stimulus is applied. The curve G gives the resultant change in the resistance of the skin of the person investigated and an upward deflection of one scale division corresponds to *a* reduction in the resistance of 20 ohm.

with the electrocardiogram directly recorded with the string galvanometer. Because this correspondence signified firstly that the earlier calculations were correct, and secondly that the new galvanometer fulfilled its purpose.

An advantage of electrocardiography over other graphic methods for the study of the heart and pulse is that the ECG can record in absolute units, and the shape of the curve no longer depends on the properties of the instrument used. Provided a string galvanometer is correctly built and is suited to its purpose, i.e. is sensitive and rapid enough, each curve, whenever and wherever in the world it may be recorded, is directly comparable to any other curve.
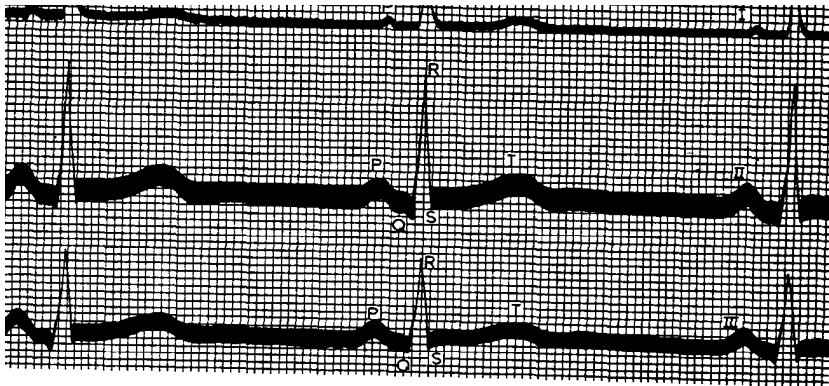

Fig. 10. Normal electrocardiogram taken with three leads simultaneously.

The investigator cannot be satisfied with the fact that he determines the shape of the potential variations at the hands and feet. This measurement is rather the means of bringing to light the functions of the heart. It is therefore desirable to take the ECG by three leads: I from the right and left hand; II from the right hand and the left foot; III from the left hand and left foot. Curves taken by these three leads have a certain relation to each other, i.e. the degree of potential variation in Lead III is equal to the difference in the potential variations recorded at the same time in Leads I and II.

$$\text{Lead III = Lead II - Lead I}$$

By means of these multiple leads it is possible to measure the direction and manifest magnitude of the potential variations in the heart itself. The technique of electrocardiography has developed so far that it is now possible to record curves with three strings simultaneously. This enables us to control the quality of the instruments and the accuracy of the methods used. For when one can confirm the formula practically by means of the curves, one demonstrates in this way that these curves have been correctly obtained.

What must we regard as the cause which determines a specific shape of the ECG or better: What determines the direction and the degree of the potential difference present in the heart at a given moment?

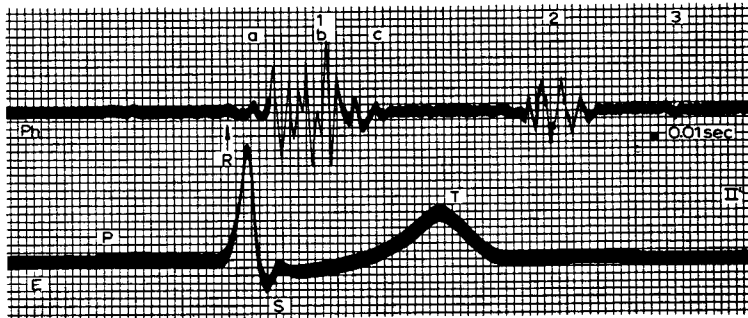The process of contraction of the heart is associated, just as is contraction

Fig. II. Heart sounds and electrocardiogram. The sounds are taken from the apex of the heart and are indicated by *1, 2,* and *3.* The third sound is only weak. In the phonocardiogram of the first sound, one can differentiate between the initial oscillations a, the main oscillations *b,* and the subsequent oscillations c. The arrow indicates both the beginning of the ventricular complex and that of the systolic heart sound. Both begin simultaneously.
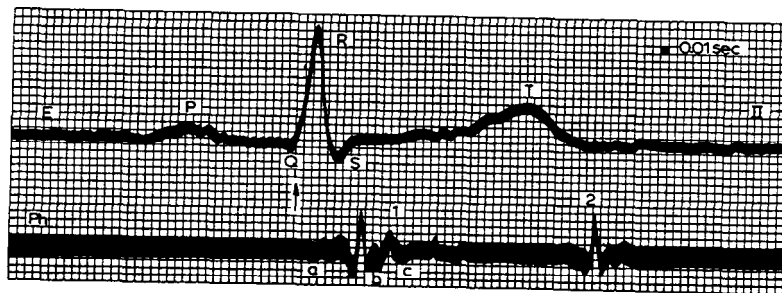
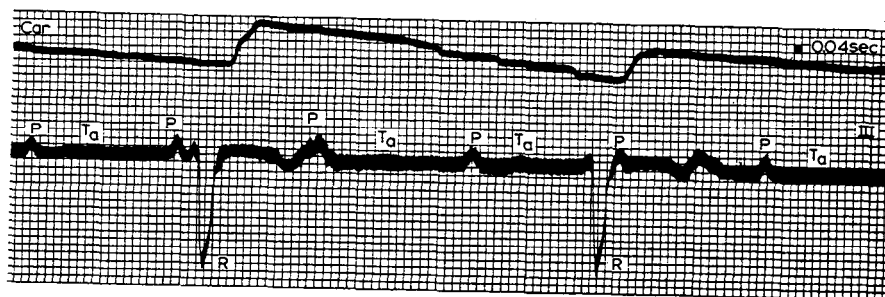Fig. 12. Similar to Fig. ɪɪ. The ventricular complex and the systolic heart sound begin almost simultaneously.

Fig. 13. Stokes-Adams disease with hypertrophy of the left ventricle. A positive T_a-wave.
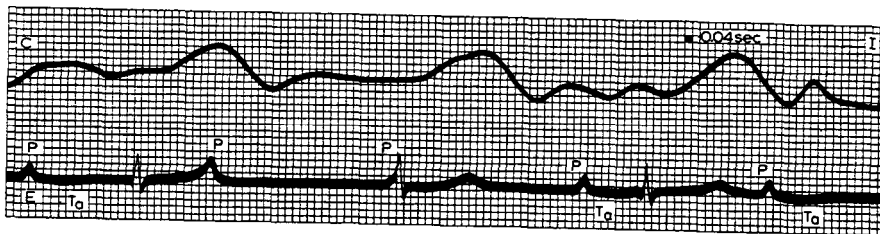

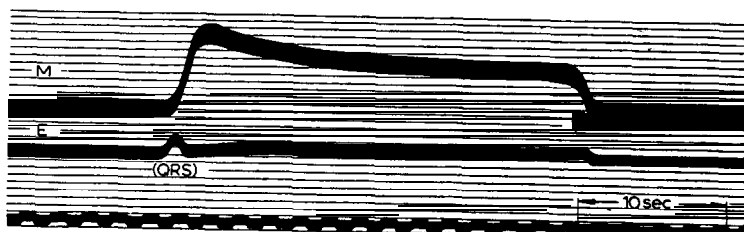Fig. 14. Stokes-Adams *disease.* The T_a-wave is negative.

Fig. 15. A frog's heart poisoned with veratrin. *M,* mechanogram; *E,* electrogram of the ventricle. The mechanical systole and the electrogram are slowed to the same degree *They* lasted almost half a minute.
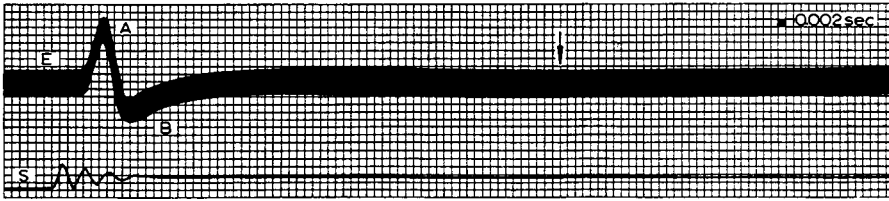
Fig. 16. Diphasic action current of a striated muscle. Stimulation at *S.* After going
through the two phases *A* and *B* there is still a late, shallow depression of the curve
visible. This is comparable to the T-wave of an electrocardiogram.

of a skeletal muscle, with the development of an electrical wave. Still the
heart as a whole may not simply be compared with a skeletal muscle. It has a
different structure. The skeletal muscle consists of fibres which are often of
the same length as the muscle itself. When a contraction wave passes over a
skeletal muscle, the locality at which the summit of the wave is found is elec-
tronegative with regard to the other parts of the muscle.

The heart muscle, however, consists of microscopically small segments,
which are separated from one another by certain septa. So far as the produc-
tion of electricity is concerned, each segment has to be considered an individ-
uality. When a contraction wave passes over a segment of heart muscle, the
point at which the summit of the wave occurs is electronegative towards all
other points in that *same* segment. Thus it is for example possible that a con-
traction wave passing over the heart at a given moment may have its summit
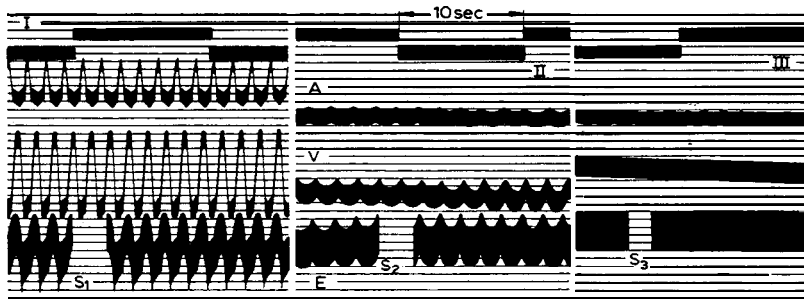
Fig. 17. Frog's heart poisoned with KCl. *I,* before the use of the KC1 solution. *II* and
III, during continued poisoning. A, mechanogram of the auricles; *V,* mechanogram
of the ventricle; *E,* electrogram of the ventricle; S_1, S_2, S_3, calibration curves. It is
evident from the curves that the mechanical and electrical phenomena decrease to the
same extent. In *III,* the summits of the ventricular systole, as well as those of the elec-
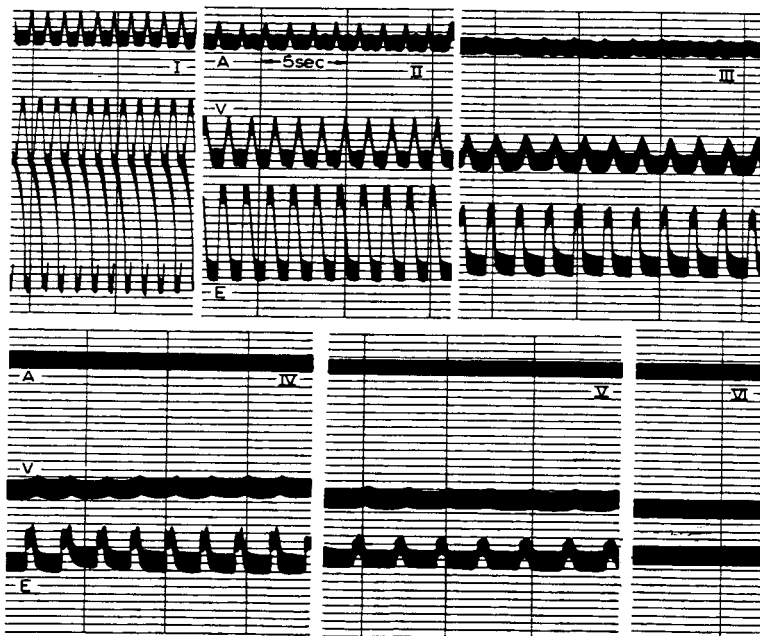trogram are just visible.

Fig. 18. Similar to Fig. 17, only the poisoning was with chloroform in stead of KCI.

in the base of the heart whilst nevertheless the direction of potential differ-
ence measured at the hands and feet indicates a negativity of the apex to the
base. For, the direction of the created potential difference is determined not
by the position of the wave in the heart, but by the position of the wave in
each individual segment.

One has also to take into account the fact that the potential difference ob-
served by indirect leads is always the resultant of all the potential differences
present in all the segments of the heart.

There is strict relationship between the electrical and the mechanical phe-
nomena of the heart systole. The accurate measurement of the moments at
which both begin is beset with difficulties, but in so far as the measurements
are made by a suitable technique and an appropriate method they indicate
that at the moment at which the electrical current begins the first mechanical
results of the contraction are also visible.

Also the duration of the mechanical contraction corresponds in general to
the duration of the production of electricity.

And finally there is also a relationship between the force of the contraction
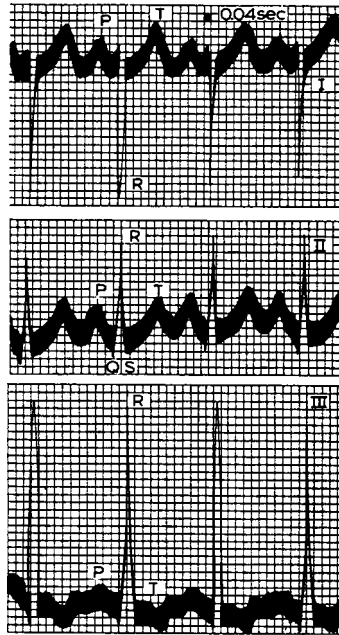and the magnitude of the potential difference produced.

Fig. 19. Preponderance of the right ventricle, negative R_I-wave and very high R_{III}-wave. The three curves were taken successively.
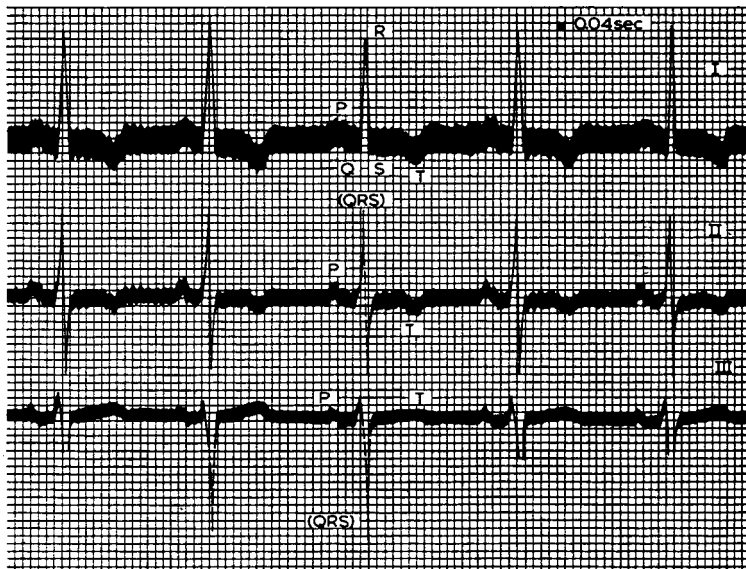

Fig. 20. Preponderance of the left ventricle. Strongly negative R_{III}-deflection. The record was taken simultaneously at the three usual leads.

In pathology and clinical work the ECG has attained great significance because it often facilitates the diagnosis of a disease. This is true for example in cases of unilateral hypertrophy of the heart.

In other cases new light has been thrown on known phenomena. As an example we can mention occasional cases in which a pulse becomes small or disappears in a series of otherwise regular successive pulses all of the same magnitude. Formerly one could think that the cause of this intermittence lies in a heart systole which because it appeared prematurely was so weak that it could not cause a forceful pulse. Now we know that also the premature systoles are of full strength and that the weakening or disappearance of the pulse is due to the fact that in the premature contraction the heart lacks time to fill its chambers with a sufficient amount of blood. A ventricle empty of blood cannot, when it contracts, even if its contraction occurs with full force, send blood into the arteries and thus cannot cause a pulse.

Fig. 21 shows a strong premature extrasystole with absence of the pulse, while some seconds later in the same patient and on the same photographic
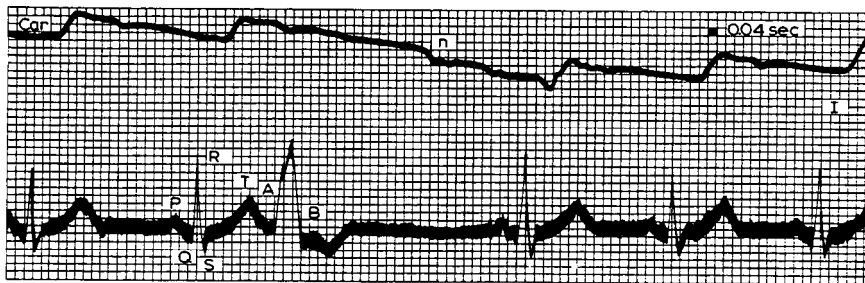

Fig. 21. Extrasystole which because of its premature occurrence caused no pulse. The heart was empty of blood during the extrasystole.
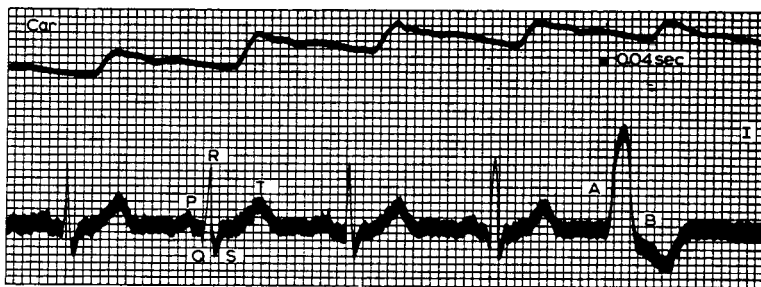

Fig. 22. An extrasystole similar to the one in the preceding figure. Because of its later appearance it caused a strong pulse. The heart had had time to fill with blood.

plate a similar but much less premature extrasystole appears (see Fig. 22). Although in both cases the kind and manner of the heart's contraction was the same, in the second case a forceful pulse was caused. This shows that what was lacking in the first case was not force but blood.

In Fig. 23 we see in succession an extrasystole *with* a pulse and one *without* it. The latter which is very premature is however very similar to the former. The atypical electrocardiograms shown in Figs. 21,22, and 23 are all laevograms. In the main they are diphasic and in Lead I the first phase is positive as in Figs. 21 and 22; in Leads II and III it is negative as in Fig. 23.

The name laevogram indicates that the curve corresponds to a systole in which the contraction begins in the left side of the heart and passes from this to the right heart. A dextrogram gives the reverse picture.

It has been doubted whether in man a diphasic action current of the heart with downwardly directed phase I in Leads II and III corresponds to alaevogram and it has been believed on theoretical grounds that the position may be the reverse. But we have by chance had the opportunity to apply a direct control in man.

There was a hitherto quite healthy man whose sternum had been surgically removed. His heart was covered only by a thin layer of skin. Light tapping on the area of the heart caused an extrasystole. Because the right half of the heart lies in man on the anterior side and thus must be stimulated mechanically by the tapping this must cause a dextrogram. Fig. 24 confirmed this prediction.

It may also be stated that this finding is in full agreement with the theory of the heart muscle segments mentioned above.

In many cases of disease the diagnosis is possible only by electrocardiography. This is especially true of certain diseases of the auricles and of anom-

Fig. 23. Two extrasystoles. A_1B_1 appeared late and caused a fairly strong pulse. A_2B_2 appeared earlier. Instead of the pulse corresponding to them the record shows at *n* a depression.
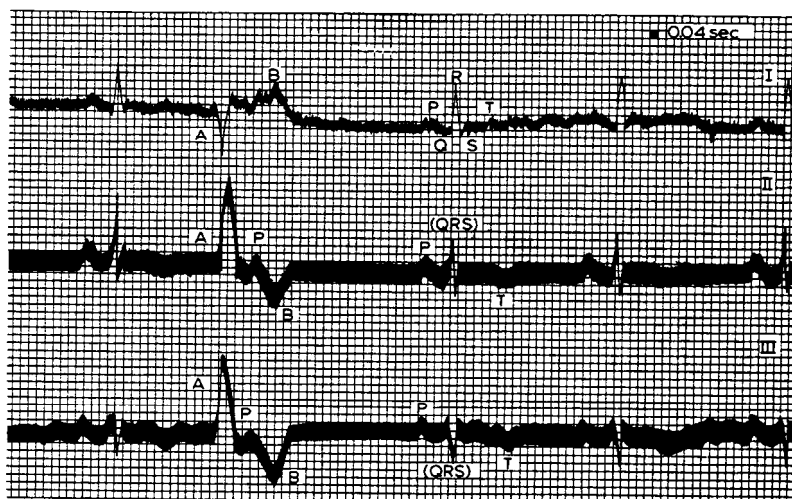
Fig. 24. Man without a sternum. The heart was as good as naked and covered only by a thin layer of skin. A light tapping on the heart area caused an extrasystole. This is a pure dextrogram which is in agreement with the theory that the segments of the heart muscle are electrically to be regarded as being individual entities.

alies in various parts of the conduction system which can nowadays be accurately localized.

I may be permitted to return in a few words to the capillary electrometer.

In 1894 we recorded with this instrument an ECG which had a shape markedly diverging from curves up till then recorded, which puzzled us. The oscillations of the mercury meniscus were so slow that the recorded curve must in itself already reproduce approximately the variations in potential actually present. Thus a detailed calculation and construction were not carried out.

In the course of 1925 we had the opportunity to investigate the same person who is now 79 years old with the string galvanometer. In Figs. 25 and 26 one sees how closely the capillary electrometer curve taken with Lead I 31 years earlier corresponds to the galvanometric curve taken with the same lead.

The typical heart anomaly has remained unchanged all this long time but what was then a puzzle is now explained. The patient had a block in the left branch of the bundle of His. The ventricles execute abnormal contractions and produce dextrograms. Clinically it is important that a patient can have this anomaly for more than 31 years without experiencing excessive discomfort and this case is for that reason alone well worth mentioning because un-

Fig. 25. Record of an electrocardiogram by means of a capillary electrometer taken on June 15, 1894, i.e. before the construction of the string galvanometer. Lead I. Blocking of conduction in the left branch of the bundle of His. Aberrant dextrogram.

til now clinical work on the whole has had at its disposal only experience in electrocardiography of limited duration.

The insight into the true nature of the deficiency has been given to us by later investigators. Among them the English investigator Thomas Lewis, who has played a great part in the development of electrocardiography deserves special mention. It is my conviction that the general interest in ECG would certainly not have risen so high, nowadays, if we had had to do without his work, and I doubt whether without his valuable contributions I should have the privilege of standing before you today.
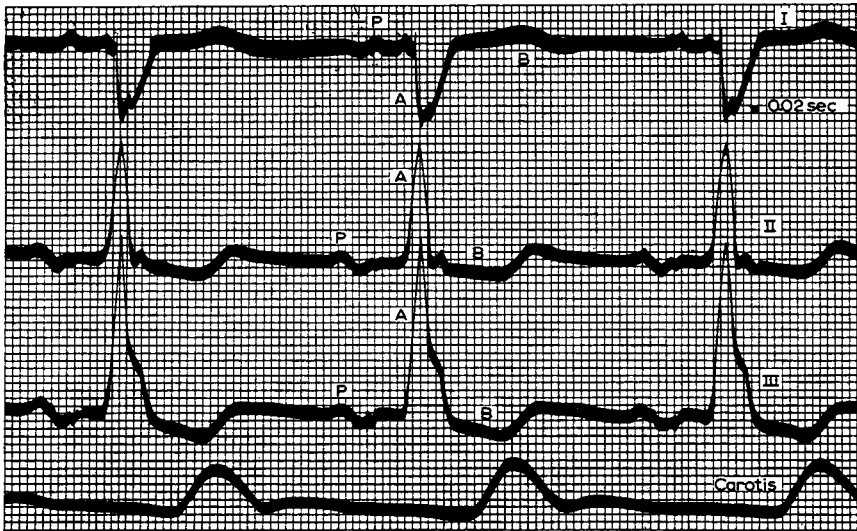

Fig. 26. The same patient as in Fig. 25 but investigated 31 years later with three leads simultaneously. The disease has remained unchanged. One notes the similarity of the curves taken with the capillary electrometer and the galvanometer with Lead I.

But in addition, innumerable other workers in the field of electrocardio-
graphy have gained great merit. We cannot now name them all but we
conclude with a reference to the happy circumstance that investigators of the
whole world have worked together. A new chapter has been opened in the
study of heart diseases, not by the work of a single investigator, but by that
of many talented men, who have not been influenced in their work by polit-
ical boundaries and, distributed over the whole surface of the earth, have
devoted their powers to an ideal purpose, the advance of knowledge by
which, finally, suffering mankind is helped.