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A study of the movements of the heart and their relationship to the filling of the auricles.

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A STUDY OF THE MOVEMENTS OF THE HEART AND
THEIR RELATIONSHIP TO THE FILLING OF THE AURICLES.

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CONTENTS.

A STUDY OF THE MOVEMENTS OF THE HEART AND
THEIR RELATIONSHIP TO THE FILLING OF THE AURICLES.

The movements which various parts of the heart undergo are
not easily observable in the intact animal, and for this reason
their significance has not been wholly understood. Three cent-
uries ago Harvey (1) stated that he almost believed that the
motion of the heart was to be understood by God alone. However,
he described it as becoming narrower and longer as it contracts,
but other observers have shown that a shortening really occurs.

It is easily seen by direct observation of the exposed heart
in a living animal, that the systolic shortening of its longit-
udinal axis occurs not by a lifting of the apex, but by a down-
ward movement of the base. This was first observed by Leonardo da
Vinci (1452-1519), who stated that "if three needles be passed
through the chest wall so that their points lie, one in the base,
one about the middle of the ventricles, and one in the apex of the
ventricles, each ventricular systole is accompanied by a downward
movement of the needle in the base of the heart, a slighter
downward movement of the middle needle, and practically no move-
ment at all of the needle which is thrust into the apex"(2).

Haycraft (3) in 1892 by the same method obtained the same
results on the heart of the cat and rabbit. Wiggers (4) also
describes this downward movement of the base of the heart during
systole and attributes the sharp fall during ventricular systole
of his intra-auricular pressure curves to this cause.

Lewis (5) describes the movement of a bullet lodged in the
heart of a man. From x-ray examination the bullet was believed

to lie in the interventricular septum. It was nearer the apex than the base of the heart, and with each systole it showed a slight downward movement when viewed laterally.

If the chest wall of an intact frog is carefully observed, a slight pulsation can be seen at each heart beat, but this slight movement is by no means comparable to the volume of blood which flows from the heart at each beat. Since the tissues forming the anterior chest wall in the frog are thin and easily movable, it seems that the total volume of the heart must be remaining almost constant during systole, or there would be a more marked pulsation of the chest wall. In order for the total heart volume to remain constant during systole, blood must be filling the auricles completely during the same period that the ventricle is emptying.

When the heart is exposed, a movement of the organs surrounding it would be observable at each systole if this were not the case. Such a movement would be wasting the energy of the heart. However, observation shows that very little movement of the organs surrounding the heart really occurs, because the downward movement of the auriculo-ventricular septum at each systole allows the auricle to fill during this period. The heart is thus enabled to expend its energy in moving blood, instead of wasting some of it in moving the surrounding organs.

Procedure: A direct study of the movements of the heart of the frog, turtle, and dog was made. The movements were recorded by means of levers of the type shown in Fig. 1.
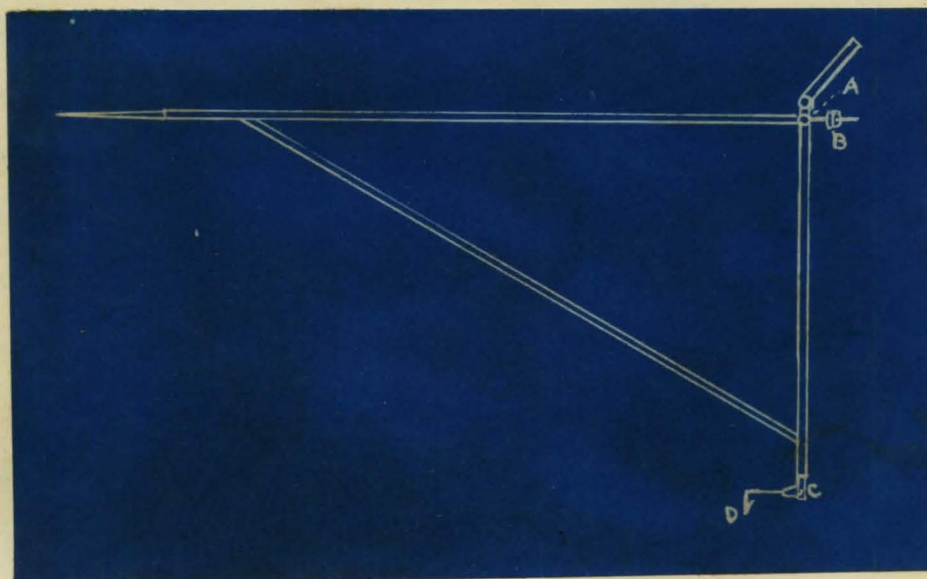
Fig.1. Drawing of lever used to record movements of frog, turtle,
and dog heart. Magnification is 2:1. A- Pin pivot. B- weight
used for counterbalancing lever. C- hinge used to prevent
movements other than toward the head or tail from being recorded.
D- barb used to hold wire in heart.

The levers were constructed of thin strips of balsa wood,
care being taken to prevent excessive weight. The pin type of
pivot was used to minimize friction, and the levers were counter-
balanced by small weights. Attachment to the heart was made by
means of a hinged wire arrangement, which allowed only movements
toward or away from the head to be recorded. A small metal barb
was soldered to the end of the wire so that it could not slip
out of the heart muscle. The writing point on the lever was a
thin strip of celluloid. Recording was done on a kymograph drum
covered with cellophane smoked over a kerosene flame. The records

when fixed by passing through a bath of thinned shellac and dried, were printed upon either blueprint paper or photographic paper. Slides for projection purposes were made by putting sections of the records between pieces of thin glass. Visscher (6) describes a method of using cellophane for recording in which a compressed air spray is used for blackening and fixing the drums. However, I found it unnecessary to use this method, as the usual method of blackening and fixing was found to be entirely satisfactory for cellophane.

In order to make a study of the movements of the frog heart, two levers were used simultaneously. The frog was first pithed, and then the heart carefully exposed. The pericardium was opened, and then one of the small metal barbs of one lever was thrust into the base of the heart, while the other lever was connected to the apex by the same method. The levers were so arranged that the upper writing point would record cephalad and caudad movements of the base, while the lower writing point recorded corresponding movements of the apex. A downward movement of either writing point indicated a caudad movement of the corresponding part of the heart. The levers were so constructed that the writing points inscribed twice the movement actually made by the point on the heart. A record of the movement of the base and apex of the frog's heart is shown in Fig.2. It is seen that the movements of the base are much greater than those of the apex. By observation it was found that at each systole of the ventricle, the base of the ventricle moves toward the apex, while the apex itself remains practically stationary.

Fig. 2. Movements of base and apex of frog heart. Lever magnification was 2:1. Time was recorded in 1" intervals. Observation showed that the downward movement of the base occurred during systole.

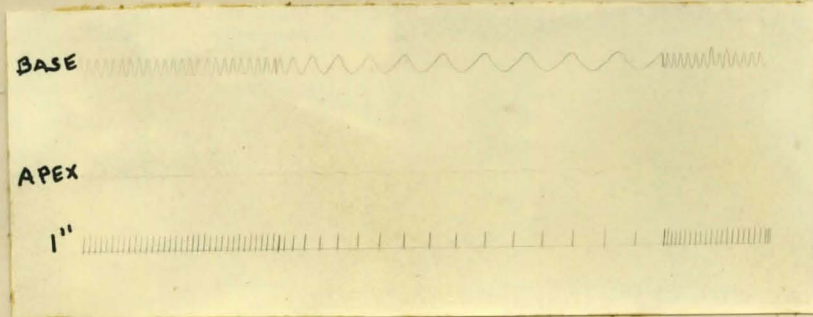Fig. 3 shows the same thing as Fig. 2. except that a larger movement of the base was recorded because a larger frog was used.
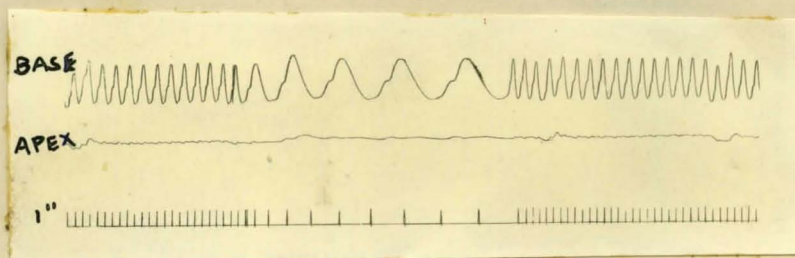
Fig. 3. Movements of base and apex of frog heart. Lever magnification was 2:1. Time was recorded in 1" intervals.

A study of the movements of the turtle heart was made by
the same method, and it was found, as shown in Fig.4, that the
base had a large caudad movement during systole, while the apex
had only a slight movement cephalad. Cutting the frenulum caused
the whole heart to move upward slightly, but the apex moved
cephalad much more than the base, thus causing the longitudinal
axis of the heart to be shortened. Also, cutting the frenulum
caused the movement of the base to be very much reduced, while
that of the apex was usually slightly increased.

Fig.4. Movements of turtle heart. Lever magnification was 2:1.
Lower record shows effect of cutting frenulum. The base and apex
both moved cephalad. Movements of the base were reduced greatly,
while those of the apex were hardly changed.

CONSIDERATION OF FUNCTION OF FRENULUM.

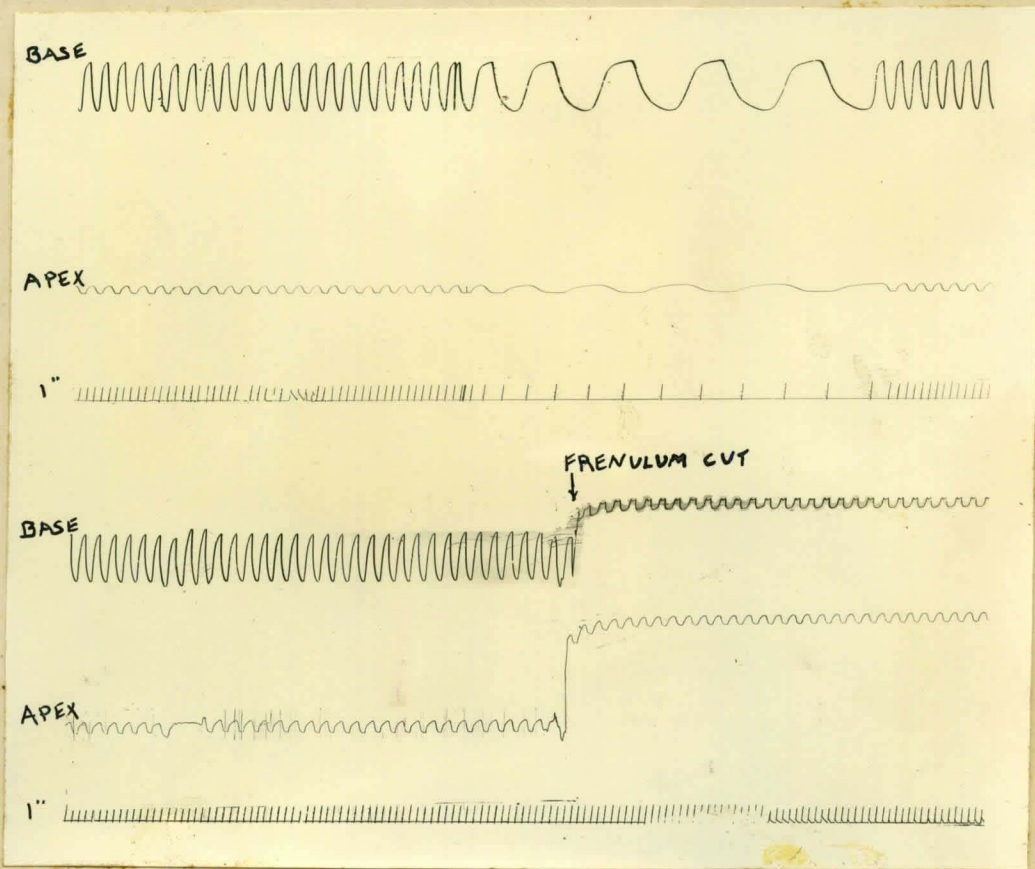In the previous studies on the frog heart it was found that
cutting the frenulum has very little effect, but this is to
be expected since it is not as highly developed in the frog as
in the turtle heart. In the frog heart the frenulum consists
merely of several delicate strands of connective tissue connect-
ing the posterior surface of the ventricle to the pericardium,
while in the turtle heart the frenulum attaches the tip of the
ventricle to connective tissue, which ensheaths the liver and
which also has attachment to the anterior body wall. The funct-
ion of the frenulum seems to be to "anchor" the apex, for each
systole of the heart causes a pull upon it which is transmitted
to the body wall. This fixation of the apex allows the ventric-
ular musculature to pull the base downward at each systole, for
cutting the frenulum reduces the caudad movement of the base
markedly. The heart is thus enabled to expend its energy in
moving blood, instead of wasting part of it in moving the surround-
ing organs.

In the mammalian heart the frenulum is absent, but its
function is accomplished by other means. The mediastinum offers
considerable support to the heart, and the pressure exerted
upon it by the lungs also aids in maintaining its position.
Mackenzie (7) has shown that the apex of the heart is closely
adherent to the diaphragm, and that it is held practically
stationary because of the inertia of the heavy abdominal organs.
He has shown that there is a slight upward movement of the liver
during ventricular systole, but the weight of that organ makes
the movement very slight.

In studying the movement of the dog's heart, the same method was used, but stronger levers were employed. The chest was open-ed in the mid-line, and artificial respiration given. The peri-cardium was opened, and one of the levers was connected to the base by the usual arrangement, while the other was connected to the apex. A pulse tracing was also recorded by placing a glycerin capsule over the femoral artery, and connecting to a Becker tambour. The record shown in Fig.5 indicates that there is about a 1½c.m. movement of the base caudally during systole, while the movement of the apex is very slight.
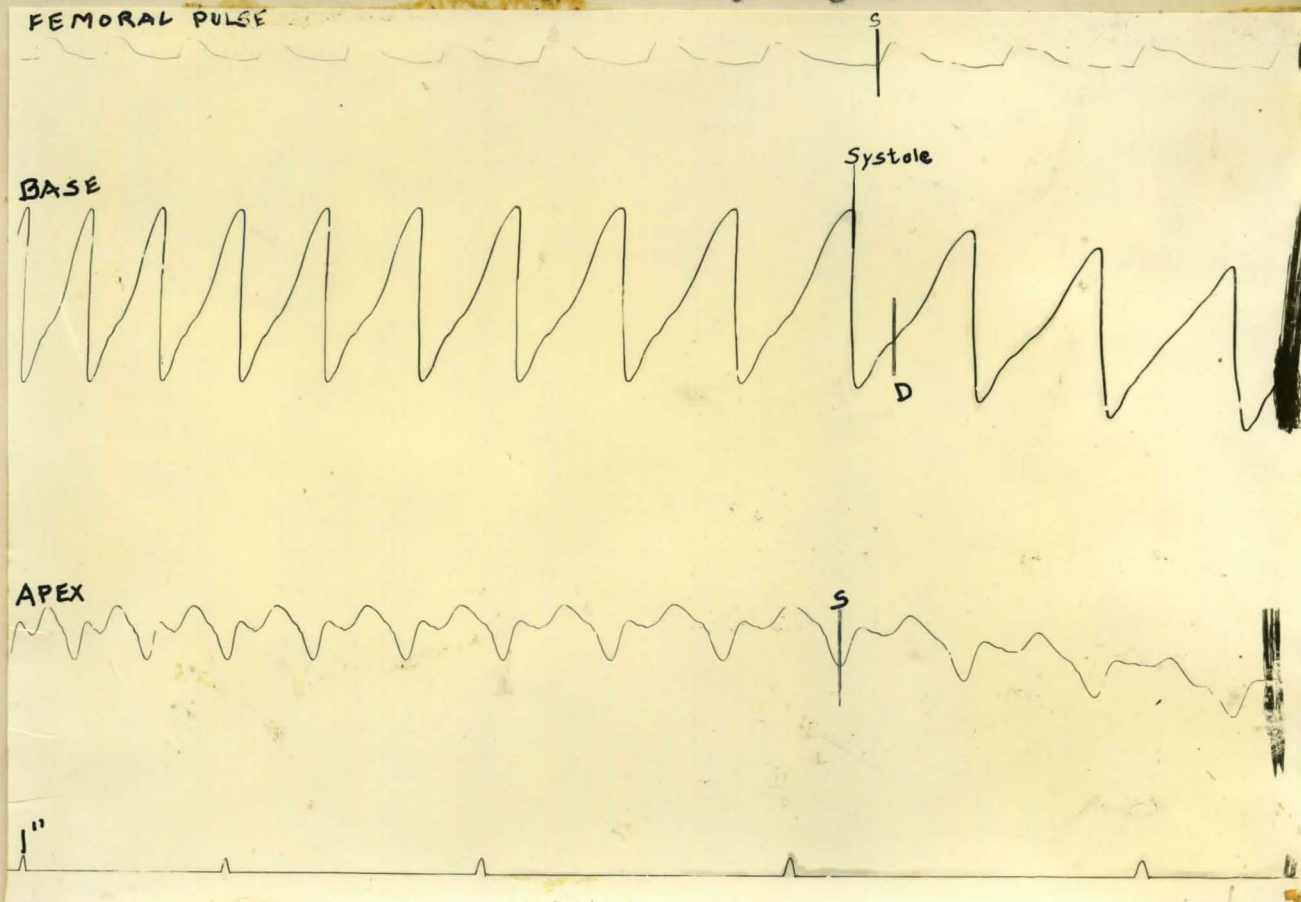
Fig.5. Movements of dog heart. Upper tracing is femoral pulse, the second shows movements of base of heart, the third shows movements of apex, while the lower tracing indicates time in seconds. Perpendicular lines show duration of systole on each tracing. Magnification of levers was 2:1.

Allowance must be made in this experiment for the fact that the chest was open, and thus the heart was more free to move than in the intact animal. The slight upward movement of the base toward the end of systole indicates a movement of the whole heart. This is due to the fact that the previously distended aorta diminishes in size and thus pulls the heart upward. During diastole the auricular size diminishes, as the auriculo-ventricular septum moves upward.

FLUOROSCOPIC STUDY OF THE MOVEMENTS OF THE HEART.

The studies by mechanical means of the movements of the heart of the frog, turtle, and the dog showed that there is a relatively large movement caudally of the base of the heart during systole, while the movements of the apex are only slight, varying in the frog and turtle according to the development of the frenulum. However, in all these cases the heart was exposed, and therefore, in order that conditions might be as normal as possible, the fluoroscopic method suggested itself for further study of the movements.

The x-ray silhouette gives us an excellent picture of the movements of the outline of the heart as a whole, but does not differentiate between the auricle and ventricle. Therefore, in order to study fluoroscopically the movements of the base, small pieces of metal were placed in various parts of the A-V groove, and also in the apex. Barbs were cut from medium sized fish hooks, and the shaft part of each was ground to fit the end of a four inch, eighteen gauge needle. These were then pushed through the chest wall of a dog under ether anaesthesia, while observing the heart fluoroscopically. The barbs were thrust into the heart wall, and then dislodged from the needle by a stylet. When the needle was withdrawn, they remained in the heart, because their shape would not allow them to move backward. The movement of the barbs was observed fluoroscopically and charted, and finally their exact position within the heart was determined at autopsy. By this method it was found that during systole the base of the heart of a medium-sized dog moved caudally about 1c.m., while the apex had only a very slight movement.

An operative method was then undertaken in placing metallic objects in the heart of dogs, so that their position could be known without first killing the animal. In this method the dogs were given ½ grain morphine sulphate hypodermically, and then the entire chest wall was carefully shaved and washed. Ether anaesthesia was given, and the chest was opened in the midline, the operation being done under aseptic technique. Artificial respiration was given through a metal mask, which fitted the dog's head air-tight. The objects placed in the heart were ½c.m. pieces of #16 silver wire, which were first placed inside a large bore needle. The needle was then thrust obliquely into the heart wall, and the silver wire dislodged by a stylet. A series of the objects were placed along the basexof the heart and several were placed in the apex. Three dogs survived the operatioh, and fluoroscopic and radiographic examination was made of each. Results of the fluoroscopic examinations are shown in Fig.6. Fig.7 is an x-ray picture which shows the position and movement of the objects within the heart of one of the dogs. The results of the Fluoroscopic and x-ray studies show that in the intact dog the movements are in accord with the findings by direct recording, that is, the base of the ventricle moves caudally about one centimeter at each systole, and this causes the ventricular walls to thicken, for the apex is almost stationary. However, systole also causes a movement of the anterior and posterior walls of the ventricle toward each other. The net result of these movements enlarges the auricular cavity, and reduces the ventricular cavities to a minimum, thus most efficiently expelling their blood from them.
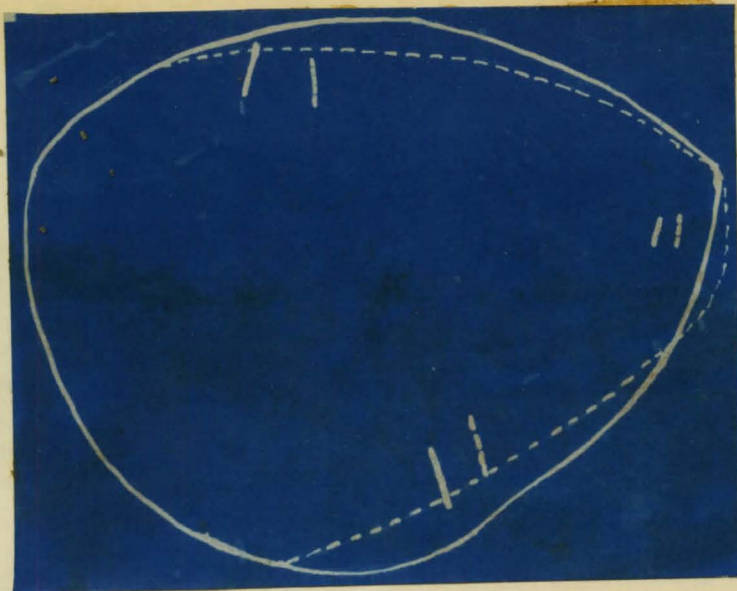
Dog #1. Right
Lateral view of
heart as shown
by fluoroscopic
examination.
Solid lines show
diastolic position.
Dotted lines show
systolic position.
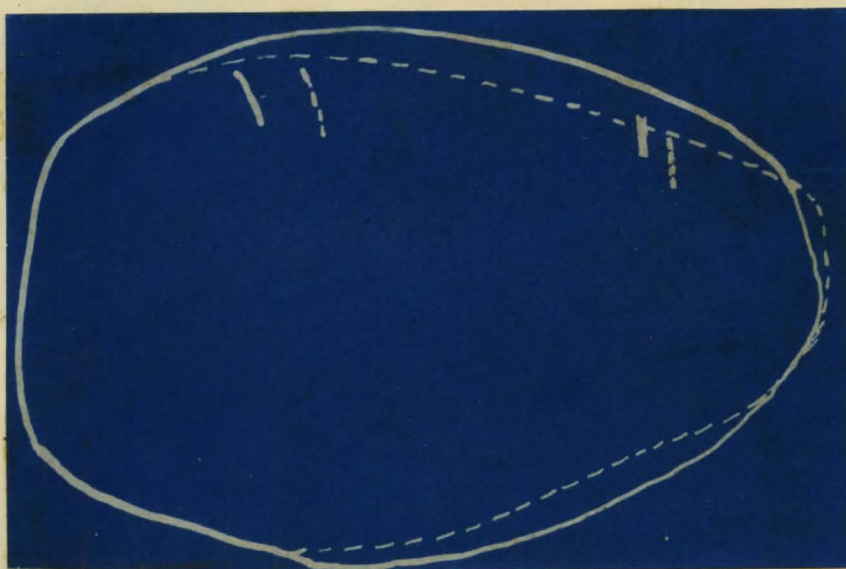
Dog.#2. Right lateral
view of heart as
shown by fluoroscopic
examination. Solid
lines show diastolic
position. Dotted lines
show systolic posit-
ion.
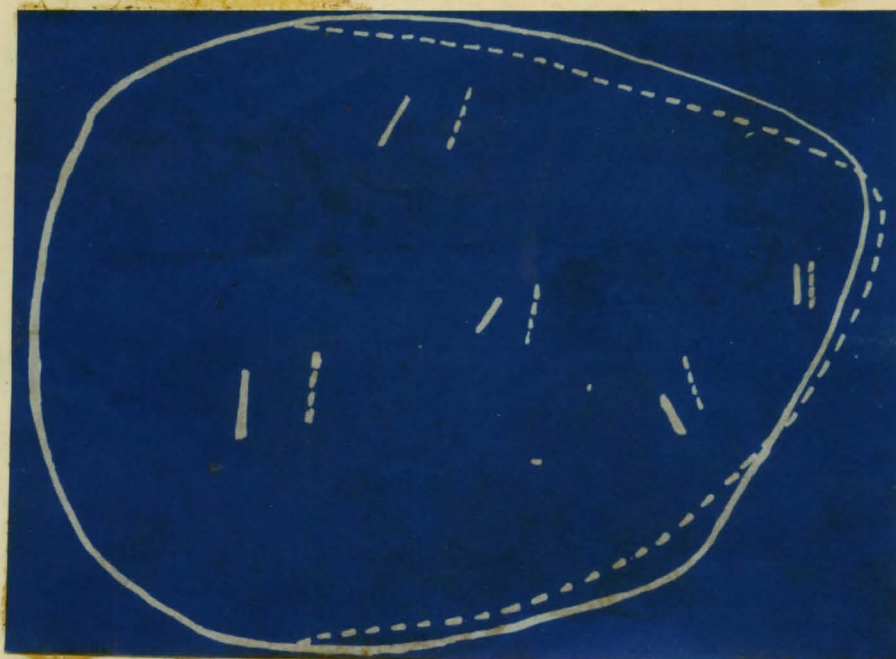
Dog.#3. Right lateral
view of heart as
shown by fluoroscopic
examination. Solid
lines show diastolic
position. Dotted lines
show systolic position.

Fig. 6. Drawings showing results of fluoroscopic studies of heart movements.

Fig. 7. Radiograph of right lateral view of heart of dog #3
showing systolic and diastolic positions of silver wires.
The heart rate was 60 per minute. X-ray exposure was 4
seconds. Much greater movement is shown by the wires in
base of heart. Large wire loops are silver wires inserted
to hold sternum together during recovery. #1- wire in base
of heart, diastolic position. #1'- same wire, systolic
position. #2- silver wire in posterior part of base of
ventricle, diastolic position. #2'- same wire, systolic
position. #3- silver wire in posterior part of heart,
diastolic position. #3'-same wire, systolic position.
#4 silver wire in posterior part of apex, diastolic pos-
ition, #4'- same wire, systolic position. #5- wire in tip
of apex, diastolic position. #5', same, systolic position.

CONSIDERATION OF THE SIGNIFICANCE OF FLUOROCOPIC FINDINGS+

Several attempts (8, 9) have been made to determine the stroke volume of the heart by calculations which have as their basis the difference in area of the systolic and diastolic shadows as shown by x-ray pictures. In this method x-ray photographs of about 1/40 second exposure are made during the R wave of the electrocardiogram and at the end of the T wave. The area of the shadows is measured with a planimeter, and the volume computed by means of Bardeen's formula ($V= .53A^{3/2}$). Hodges (9) has attempted to improve the method by using a photo-electric cell to close the circuit in making the x-ray exposures, which in his method are 1/400th second in duration.

Meek and Eyster (8) found by their x-ray method that during exercise the diastolic and systolic size of the heart may increase or decrease, but that usually the stroke volume is increased. They found however, that in some cases there was an increased output per beat although the diastolic size was decreased. They attributed this to changes in tonus of the heart musculature. Meek (10) in 1924 found that a normal resting dog's heart throws about as large a diastolic shadow when beating at a rate of 110 as it does at 60, and at the same time at the rapid rate puts out much less blood per beat (11) However, he found that as the rate increases beyond an average of 110, the diastolic size undergoes a rapid decrease, but if the venous pressure is maintained by perfusion the rate may be increased as high as 200 per minute without any decrease in the diastolic size. In this work Meek used the same method as before except that he used Skavlem's formula (12) which is a modification of the Bardeen formula for use on dogs, to calculate the heart volume from the area of the diastolic heart shadow.

The x-ray method for determining the cardiac output as used by Meek and Eyster, and Hodges is incorrect, because they were determining the changes in area of the heart shadow as a whole, and not that of the ventricles. The auricle can not be distinguished from the ventricle by x-ray examination. Also, the base of the ventricle has a greater movement caudally during systole than the upper border of the auricles, and this indicates that the total volume of the heart does not change as much during a heart cycle as its stroke volume would indicate. Therefore, during ventricular systole the auricles must be filling or the total volume of the heart would change appreciably. This filling of the auricles is accomplished by the downward movement of the auriculo-ventricular septum, which during ventricular systole enlarges the cavity of the auricles, and thus allows a flow of blood into them from the great veins.

This view gives us an explanation as to how a slow heart may pump the same amount of blood per minute as a fast one, and yet give the same size shadow on x-ray examination. The slow heart with the large stroke volume probably has large ventricles and small auricles, and the rapid heart probably has more blood in the auricles, but the ventricle takes a smaller proportion of the auricular blood at each beat.

Meek and Eyster (8) have found that the diastolic heart shadow remains about the same during exercise, but Henderson and Haggard (13) and most other authorities have found that the stroke volume is increased. This problem can be explained if we assume that the rapid filling of the auricle during ventricular systole enables the heart to pump more blood at each beat without

increasing its diastolic size. This explanation assumes that the higher venous pressure during exercise fills the auricles more completely during ventricular systole, and they in turn are able to fill more completely the ventricles.

The finding that the base of the ventricle makes such a marked caudad movement during systole led me to make a study of the volume changes occurring in the heart as a whole, and the auricle and ventricle separately, to determine if there is any relationship between the movements and volume changes of the heart.

A STUDY OF VOLUME CHANGES IN THE HEART
WITH PARTICULAR REFERENCE TO THE FILLING OF THE AURICLE.

Current physiology texts state that the auricle merely acts
as a reservoir to receive the blood from the great veins, during
the period when the A-V valves are closed (14). Most texts state
that the flow of blood into the chest occurs throughout the heart
cycle, except during auricular systole. Hamilton (15) has obtained
evidence from the cardiopneumogram that the flow of blood into
the thoracic cavity during ventricular systole is very nearly
equal to the outflow. He also obtained evidence from the abdominal
plethysmogram that during ventricular systole the abdominal size
diminishes in spite of the arterial expansion, thus indicating
that the blood in the abdominal veins flows toward the heart
during systole. Holzlöhner (16) has recorded cardiopneumograms
by means of hot wire anenometers, and has found gross volume
changes of as much as 35c.c. in the thoracic cavity during vent-
ricular systole. However, his net changes during systole amount
only to about 5 c.c., and thus agree roughly with Hamilton's
findings.

Henderson (17) and numerous other investigators have studied
volume changes of the ventricle by means of a cardiometer and
have obtained much evidence concerning the filling of the ventricle
under various conditions. Henderson's view is that the ventricle
fills during diastole by a flow of blood from the veins.

Stefani (18) recorded changes of volume of the whole heart
using the pericardium as a cardiometer by simply inserting a
cannula into it and connecting with a tambour, using air trans-
mission. Stefani's volume curves of the whole heart differ from
the ventricular volume curves of Henderson and others in having

several waves for each heart cycle. The usual type of curve
obtained by Stefani consisted of a sharp downstroke during vent-
ricular systole, and then an upstroke which was in two phases.
Stefani interpreted the downstroke as being due to ventricular
systole, and the first phase of the upstroke as being due to
diastole. However, he did not publish a simultaneous pulse tracing,
and therefore, it is not certain that the first phase of the
upstroke really occured during diastole. Also, from his Curves
it is apparent that he did not allow a sufficient time for vent-
ricular systole, for the primary phase of the upstroke really
appears to be within the period of systole rather than diastole.
Wiggers (19) has obtained numerous records of intra-auricular
pressure, and according to his results, there is a sharp fall in
intra-auricular pressure during ventricular systole. Fig. 8 gives
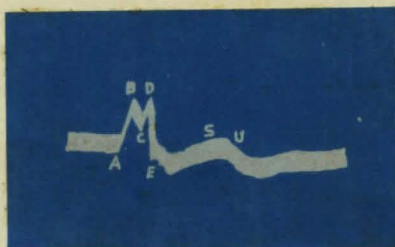a typical intra-auricular pressure curve as recorded by Wiggers.

Fig. 8. Record of right intra-auricular pressure as recorded by
Wiggers. (Page 32, Pressure Pulses In the Cardiovascular System)
A-B-C, auricular wave; C-D-E, early systolic wave; S, end of
ventricular systole; U, onset of right ventricular inflow.
R Burton-Opitz (20) by measuring the flow of blood through the
external jugular vein has found that the flow is ten times as
great during the period B to E on Fig.8 as it is at any other
part of the cardiac cycle.

PROCEDURE A study of the volume changes was made on the frog,
turtle and dog heart. The apparatus shown in Fig.9 was used to
record the volume changes of the frog and turtle hearts. The
tambours consisted of hemi-spherical shaped sacs of thin rubber,
upon which a very light lever of balsa wood rested. The lever was
partially counterbalanced and was supported by a pin pivot to
increase the sensitivity. A water manometer was connected to each
of the tambours, and the tube A connected the two. Air transmission
was used in the system, a large syringe being used to inflate
the system to the proper level, while a 1 c.c. tuberculin syringe
was used for calibrating. Suitable magnification could be obtained
by regulating the distance from the fulcrum at which the lever
touched the rubber capsule.
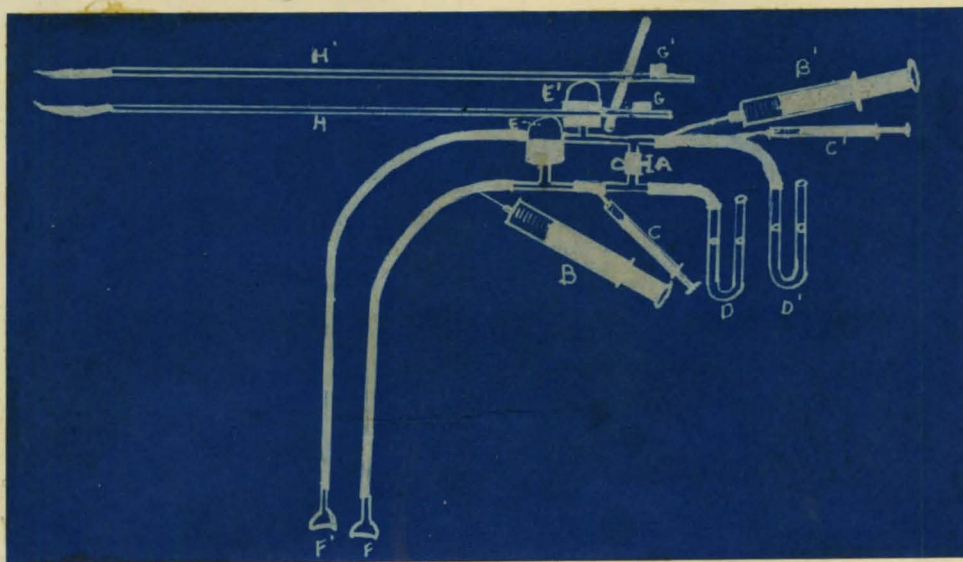

Fig. 9. Apparatus used for measuring volume changes in the frog
and turtle heart. A, tube connecting the two systems. B & B',20c.c
syringes. C & C', 1c.c. tuberculin syringes used for calibrating.
D & D', water manometers. E & E', thin rubber tambours. F & F',
glass cup cardiometers, G & G', small weights used to partially
counterbalance levers. H & H', Balsa wood levers.

For the study of the frog's heart large male frogs weighing from 1 to 1½ kilos were used. The frogs were first pithed, and then the heart was exposed, care being taken to avoid hemorrhage. A large bore glass cannula was then inserted into the pericardium and connected to one of the recorders. Enough air was injected into the system to distend moderately the pericardial cavity, but not to raise the pressure over 2m.m. of water. A record of the volume changes as shown in Fig.10 was obtained. Calibration was made by injecting .1 c.c. portions of air into the system and then withdrawing them.

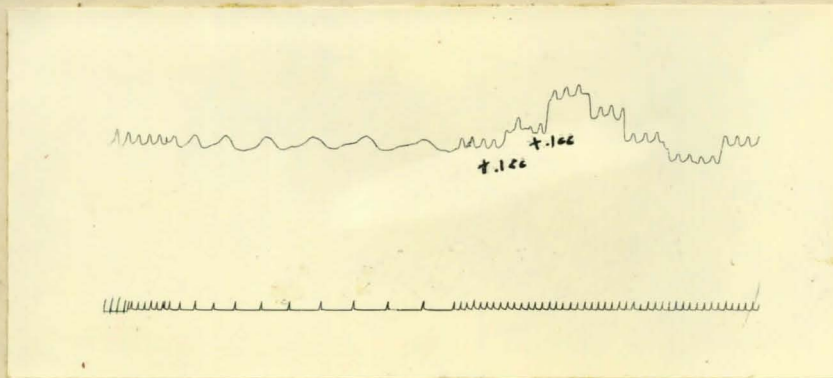Fig.8. Volume changes in pericardial cavity of frog. Calibration in terms of .1 c.c. air injections and withdrawals. Time is recorded in one second intervals.

Next, a small glass cup was placed over the entire heart, care being taken that it exerted but very little pressure. The cup was then connected to the volume recorder, and as shown in Fig.11 the records obtained were very similar to those obtained using the

pericardium as a cardiometer. Slightly larger volume changes
were recorded, due to the frenulum pulling tissue into the
cardiometer at each systole. However, in spite of this the
volume changes amounted to only about .1 c.c. while the
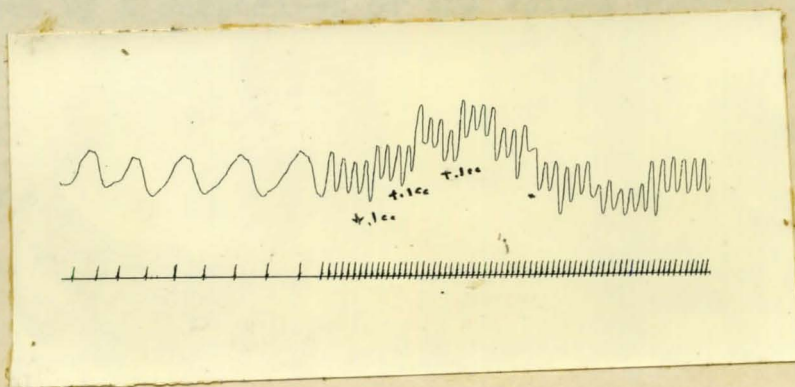average figure obtained using the pericardium as a cardiometer
was .04 c.c.

Fig. 11. Volume changes recorded in cardiometer placed over
whole heart of frog. Calibration in .1 c.c.

Simultaneous volume changes of the auricle and ventricle
of the frog's heart were then recorded. Two small glass cups
each of which had one edge flattened were used. One of the
cups was lightly placed over the auricle and connected to one
recorder, while the other was placed over the ventricle and
connected to the other recorder. The flattened edges of the
cups were contiguous, any lay in the atrio-ventricular groove.
By this means a simultaneous record of the volume changes of
the auricle and the ventricle was obtained. As shown in Fig.
12, as the volume of the ventricle decreases, the volume of
the auricle and sinus venosus increases. A very good demon-
stration of this was made by opening the tube A connecting

the recorders. Immediately the movement of each of the levers
was almost stopped, showing that the volume change in the
ventricular recorder was neutralizing that of the auricular
recorder. When the connecting tube was closed, each of the
recorders immediately inscribed its previous record. Also,
it is seen by a comparison of the volume changes shown by
either the auricular or the ventricular recorder in Fig. 12 with
the total heart volume changes as shown in Fig. 10 and Fig. 11,
that the volume change of the heart as a whole is very small
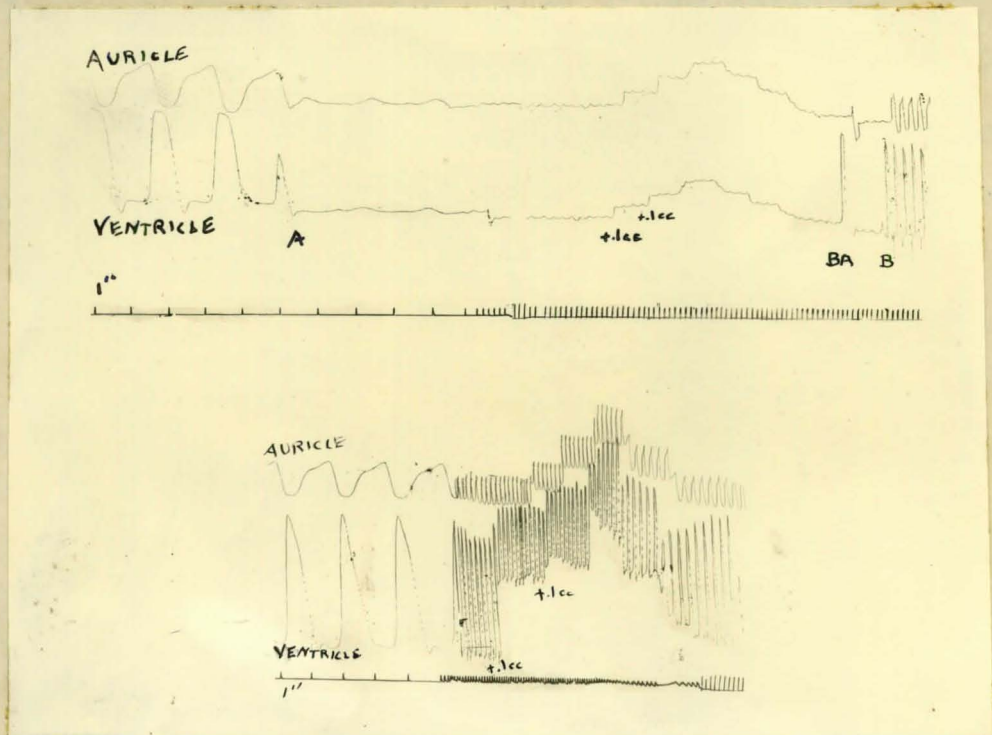as compared with the auricular or the ventricular volume
change.

Fig. 12. Simultaneous volume curves of the auricle and
ventricle of the frog heart. At A the tube connecting the
recording systems was opened. Calibration was made by .1c.c.
air injections. At B the tube was closed again. Lower record
is continuation of upper in which usual calibration was made.

Also, it must be remembered that the volume change of the auricle or ventricle alone as determined by this method is less than that occurring in the intact animal, for the slight pressure of the glass cup hinders the flow of blood. Moreover, the auricle fills more in the intact animal during systole of the ventricle, because the pressure of the cardiometer in these experiments cuts down the flow of blood toward the heart more than that away from it, because of the thinness of the walls of the veins as compared with the arteries.

When the cardiometer is placed over the whole heart very little pressure need be applied to make the system air tight, and therefore there is only a very slight impediment to the blood flow. This is shown by the fact that the volume changes determined by using the pericardium as a cardiometer agree closely with those obtained using the glass cup cardiometer.

VOLUME CHANGES IN THE TURTLE HEART+

The same apparatus was used to record volume changes of the turtle heart. Large sized turtles were used for these experiments. First, the brain was destroyed by crushing, and then the plastron was removed carefully, so as to avoid hemorrhage. A large bore glass cannula was then inserted into the pericardium and tied. Volume changes were recorded as shown in Fig. 13. Calibration was made in the usual manner.
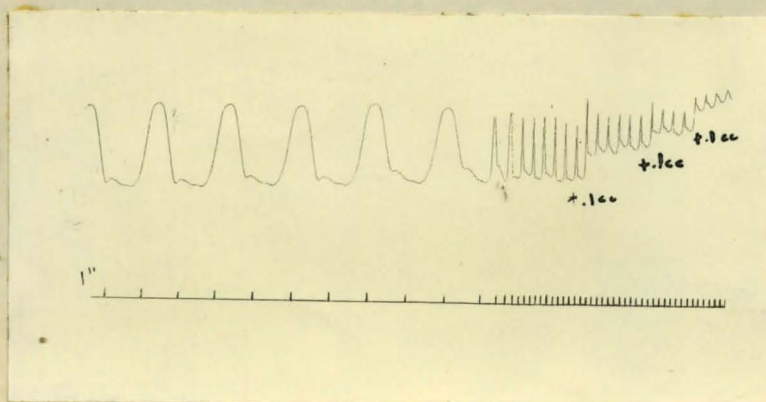
Fig. 13. Volume changes in pericardial sac of turtle. Calibration in .1 c.c. Time was recorded in 1" intervals.
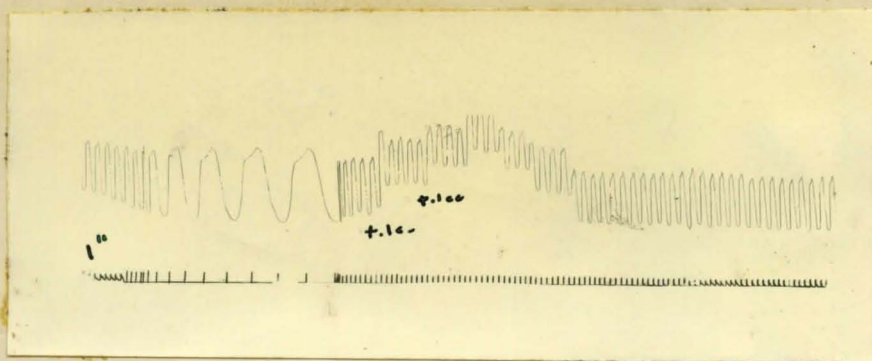

Fig. 14. Volume changes of whole heart of turtle using glass cardiometer. Calibration in .1 c.c.

The pericardium was then opened, and a small glass cup was placed lightly over the whole heart and connected to one of the volume recorders. A record of the volume changes as shown in Fig. 14 was obtained. A slightly larger volume change was

recorded by this method because at each systole the frenulum
pulled tissue into the cardiometer. However, in spite of this
the volume changes obtained using the pericardium as a card-
iometer agreed roughly with those obtained using the glass
cup cardiometer.

Finally, a record of the volume changes of the ventricle
alone was recorded by placing the glass cardiometer lightly
over the ventricle and connecting to one of the recorders.
It was necessary to cut several indentations in the edge of
the glass cup so that it would not cut off the flow of blood
in the arteries and veins. Fig. 15 is a record of the volume
changes of the ventricle alone.
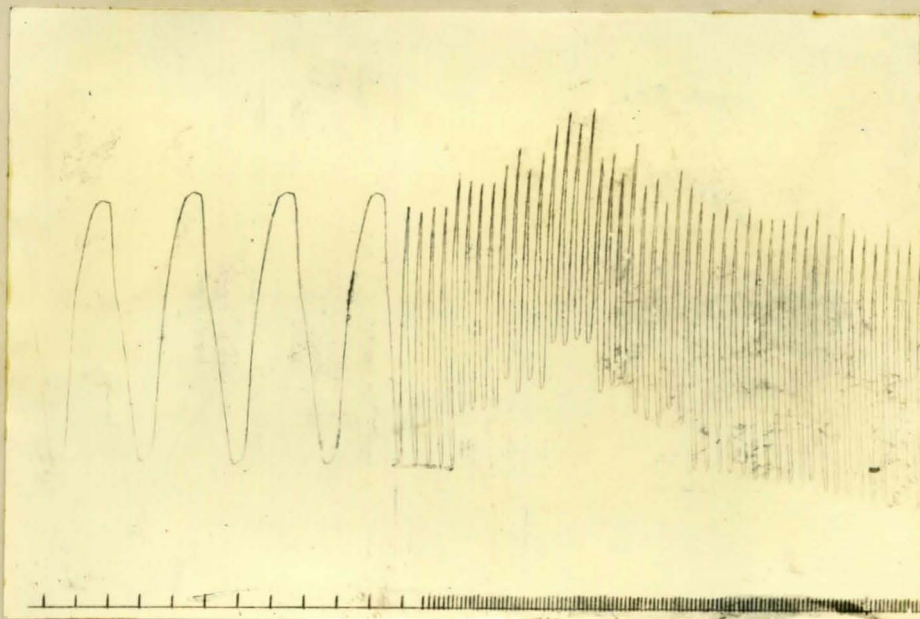
Fig. 15. Volume change of the ventricle of the turtle heart.
Calibration is in .1 c.c.

I was not able to obtain simultaneous volume change records
of the auricle and the ventricle because of the greater complex-
ity of the turtle heart. However, by comparing the ventricular
volume changes with the total heart volume changes, it is easily
seen that the auricle must be filling completely as the ventricle

empties for the volume change of the whole heart to remain so low (.2 c.c.) while the ventricular volume change is so great (.7 c.c.)

VOLUME CHANGES OF THE DOG HEART.

The dogs were anaesthetized either with ether or by giving them 200 m.g. of sodium barbital per kilo intravenously. The chest was opened in the midline, care being taken to avoid hemorrhage. Artificial respiration was given by mechanical means through a tracheal cannula. A glass cannula was inserted into the external jugular vein, and had a T tube so arranged that the venous pressure could be determined by the rise of blood within it. Connection was made to a perfusion bottle filled with warm isotonic saline so that the venous pressure could be raised by perfusion.

A cannula was inserted into the pericardium, and connected to a large tambour, which had a loose thin rubber membrane. The cannula used consisted of a threaded brass tube which had a large brass washer soldered to one end, and also another washer and nut on it. The contiguous faces of the washers were covered with rubber. A water manometer was connected into the system, so that large pressure changes in the recording system could be detected and avoided. Two syringes were also connected in the recording system, a large (50 c.c.) one to regulate the system to the proper level for recording by injection of air, and a small (20 c.c.) one for calibration of the volume changes.

A slit was made in the pericardium, and then the end of the brass cannula was buttoned through it. The loose washer was then slid down and tightened. By this means it was possible to have an airtight communication with the pericardial cavity, without much danger of the movements of the heart pulling the cannula out or tearing the pericardium.

A series of records of volume changes within the peri-
cardial cavity under various degrees of venous pressure
and also under vagus stimulation were made. A simultaneous
pulse record was taken with a glycerin capsule over the
femoral artery and recorded by means of a Becker tambour.
Figures 16, 17, 18, 19 & 20 show a series of volume curves
in which the wave due to the filling of the auricles occurs
at various places in the heart cycle. This wave is designated
V on the records. In all cases some filling of the heart
occurred before the end of ventricular systole. Care was
taken to keep the air pressure in the recording system below
1 c.m. of water pressure, this amount being necessary to
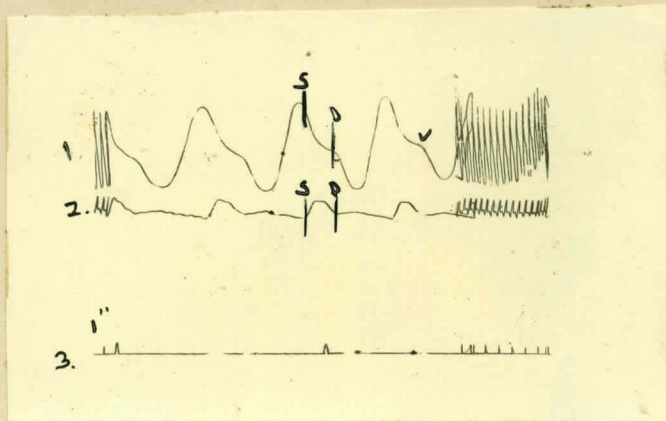distend the pericardium sufficiently for accurate recording.

Fig. 16. Volume change in pericardial cavity of dog. Heart
rate is 120. 1. Volume curve. 2. Femoral pulse tracing.
3. Time in 1" intervals. S- beginning of systole.
D- beginning of diastole. V- wave due to filling of auricles
during latter part of ventricular systole.
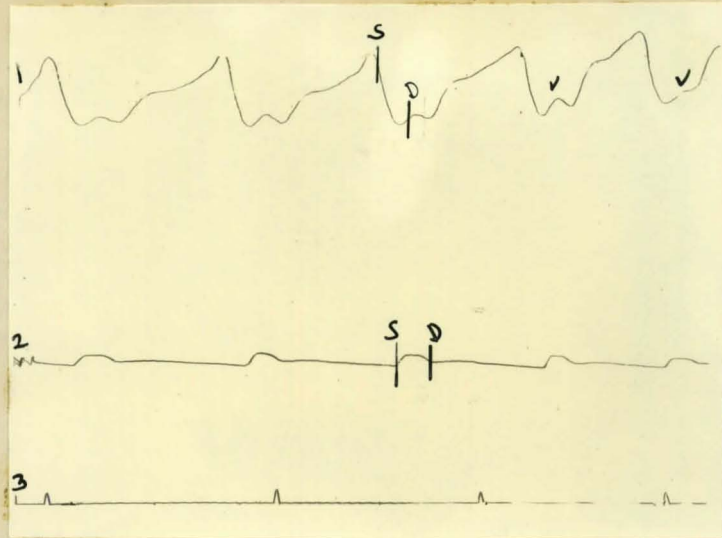
Fig. 17.   Volume changes in pericardial cavity of dog. Heart
rate is 80.   1. Volume curve;   2- Femoral pulse;   3- Time in
1" intervals.   S- beginning of systole;   D- beginning of
diastole;   V- wave on volume curve due to filling of auricles
during latter part of ventricular systole.
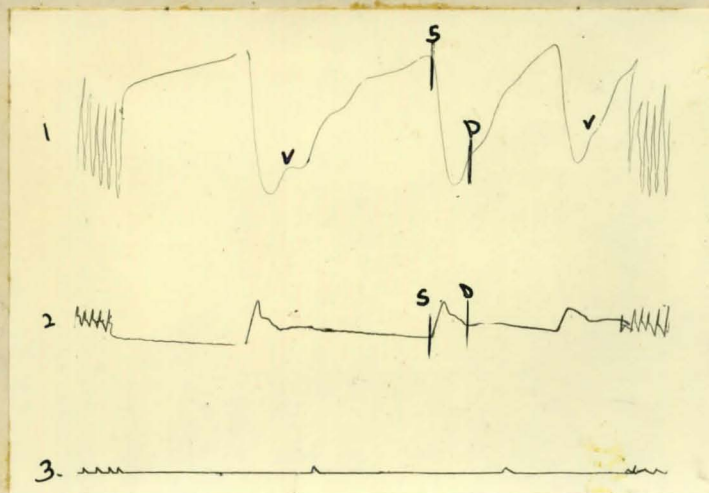
Fig. 18. Volume changes in pericardial cavity of dog. Pulse
rate is 80.   1- Volume curve.   2- Femoral pulse tracing.
3. Time in 1" intervals.   S- beginning of systole.   D- beginning
of diastole.   V- wave due to filling of auricles.

Fig. 19. Volume changes in pericardial cavity of dog. Pulse
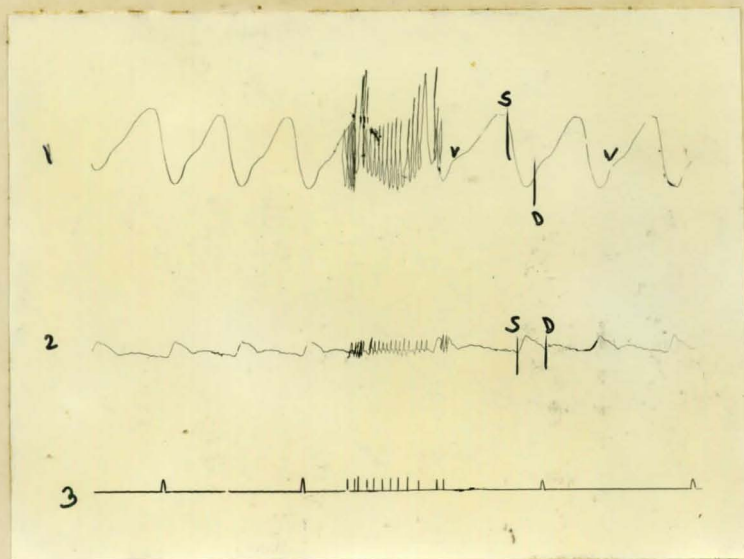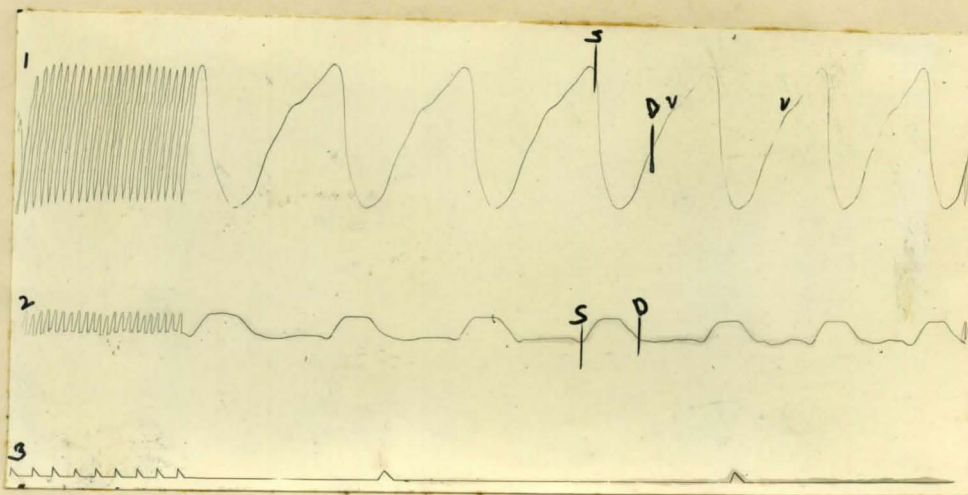rate is 120. V wave occurs later than in Fig. 18.

Fig. 20.   Volume change in pericardial cavity of dog. Pulse
rate is 120. In this tracing the V wave is very much later.

Later, in order to determine the delay in transmission og the pulse wave, a cardiometer was placed over the ventricles alone, and a volume curve of the ventricles was taken simultaneously with the femoral pulse tracing. By this means it was found that the transmission time was negligible, amounting to less than one-twentieth of a second.

It must be considered that results obtained using the pericardium as a cardiometer only indicate the tendency of the auricles to fill during ventricular systole. When the chest is open, as is necessary in plethysmographic studies, the forces and anatomical relationships which produce systolic filling of the auricles are partially removed, and the negative intra-thoracic pressure which normally aids in filling of the heart is lost.

Studies of the volume changes of the heart using the pericardium as a cardiometer may easily give misleading results. Movements of the lungs often cause them to press against the pericardium and thus give misleading volume changes. Also, sometimes the heart moves against the mouth of the cannula and closes it. This causes a recording of only part of the volume changes, a plateau being shown on the record while the cannula is closed. In most cases the respiratory movements can be stopped by producing apnea through overventilation, and if this fails curare may be used to stop all movement of skeletal muscle. Records which show artefacts due to intermittent closing of the cannula can be disregarded.

Venous pressure plays an important role in filling of the

auricles, for unless it is normal, very little filling
occurs during ventricular systole. The downward movement of
the ventricular base can fill the auricles only if there is
sufficient blood available in the great veins.

Stefani (18) divided his cardiac plethysmograms into:
(a) A rapidly descending line which coincides with the period
of systolic evacuation; (b) A rapidly ascending line which he
interpreted as corresponding with the period of active diastole;
(c) A slowly ascending line which corresponds to the period of
passive diastole and presystole. However, his first and second
periods include about one-third of the heart cycle, and thus
the second period is probably still during systole. The plethys-
mograms shown in Figs. 16 to 20 are very similar to those
obtained by Stefani, but the simultaneous pulse tracings show
that the second period of Stefani represents a filling of the
auricles during ventricular systole. As shown in Figs.16 to 20
this auricular filling may alter the volume curve of the whole
heart to a varying degree.

Cardio-pneumograms give us evidence that the intra-thoracic
volume in man varies at the most only 5 c.c. during systole,
while over 100 c.c. of blood leave the chest during that period.
Study of cardio-pneumograms gives us the same evidence for man
that plethysmographic studies give indications of in animals,
that is, that during ventricular systole the auricles must be
filling to an extent which is comparable with the amount of
blood leaving the ventricles.

CONCLUSIONS.

A study of the movements of the base and the apex of the heart of the frog, turtle, and dog showed that during ventricular systole the base has relatively great movement toward the apex, while the apex remains almost stationary, its slight movement usually being toward the base. The fact that the base of the heart has a great movement, while the apex remains almost stationary, allows the heart to expend all of its energy in moving blood, instead of wasting part of it in moving the surrounding organs. In the turtle heart especially it was found that cutting the frenulum caused a great diminution of the movement of the base, but causes a slight increase in the movements of the apex. It appears that in the heart of amphibians and reptiles the frenulum has the function of fixating the apex. In mammals the frenulum is absent, but the fact that the chest is a rigid completely filled structure makes it unnecessary, for the apex of the heart is held against the diaphragm (7). Also, in mammals the mediastinum offers greater support to the heart.

Fluoroscopic studies of dogs with silver wires placed at various points in the heart muscle confirmed in the intact animal the results obtained in acute experiments. The movements of the base of the heart downward during systole provides and explanation as to the mechanism of the filling of the auricles during that period. The base of the heart lies between the auricular and ventricular portions, and the downward movement of the auriculo-ventricular septal diaphragm enlarges the venous reservoirs allowing a flow of blood into them during

ventricular systole. As the base moves upward, the blood
accumulated in the venous reservoirs, rushes into the vent-
ricles, and thus this explains the rapid ventricular filling
which occurs.

This view that the auricles fill during ventricular systole
more completely than previously supposed is compatible with
evidence obtained from many other experiments. Wiggers, and
most other workers in the field of pressure recording, find
that during ventricular systole the intra-auricular pressure
falls to its lowest level, and also, that it gradually rises,
until at the beginning of diastole, it has reached a level
which permits rapid ventricular filling. This is shown in Fig.8.

Cardio-pneumograms obtained by Hamilton (15) and Holzlöhner
(16) show that there is no great net volume change in the
thoracic cavity during ventricular systole. This can be dem-
onstrated very simply if the mouth is filled with smoke, and
the internal nares closed with the soft palate while the resp-
iration is held at a passive expiratory standstill with the
glottis open. A series of tiny puffs of smoke issue from the
mouth, and it can easily be seen that their volume is very
minute. The simplest explanation for the fact that the intra-
thoracic volume remains practically constant during ventricular
systole is that blood is entering the chest almost as fast as
it is leaving it, the slight difference causing a pulsatile
variation of intra-thoracic volume.

Records of the simultaneous volume changes of the auricle
and ventricle of the frog heart as shown in Fig. 10 show very
clearly that the auricle fills as the ventricle empties. Also,

calibration shows that the auricle or the ventricle alone has a much greater volume change than when both are in the cardiometer together. In the turtle heart the volume change as shown in Fig. 15 shows that the ventricle alone changes its volume .7 c.c. at each beat while the whole heart volume change is only .2 c.c. as shown in Fig. 13 and Fig. 14.

Volume changes of the dog heart as recorded by tambours connected with the pericardial cavity show a wave which is called V in Figs. 16 to 20. This wave is due to the filling of the auricle and occurs near the end of systole. The rest of the upstroke on these volume records indicates slower filling of the heart, but in all cases filling of the auricles has proceeded considerably before systole is completely over.

The general conclusion arrived at as a result of study of the movements and volume changes of the heart is that during systole the base of the heart moves toward the apex, and the venous reservoirs are enlarged by this method so that a large quantity of blood flows into them before systole is over, and their elastic recoil forces this blood into the ventricle at the beginning of diastole, and is aided by the upward movement of the base.

SUMMARY.

1. Direct recording of the movements of the base and apex of the heart of the frog, turtle, and dog showed that at each systole the base of the heart makes a large movement toward the apex, while the apex remains almost stationary. This enables the heart to expend its total energy in moving blood instead of wasting part of it in moving the surrounding organs. When the frenulum of the frog or turtle heart is out, the movements of the base are decreased, while those of the apex are increased. Also, the whole heart moves upward to a varying degree depending upon the development of the frenulum.

2. Fluoroscopic observation of the heart of dogs in which silver objects had been placed showed that at each systole the base makes about a centimeter movement toward the apex, while the apex itself remains almost motionless. The movements of the base are greater than the movement of any of the borders, and this suggests that the downward movement of the base has a significance in the filling of the auricles.

3. Volume studies on the heart of the frog show that the volume changes of the heart as a whole are much less than those of the auricle or the ventricle alone. Also, simultaneous volume records of the auricle and ventricle of the frog heart show that as the volume of the ventricle decreases, the volume of the auricle is increasing.

4. Volume studies of the heart of the turtle show that the volume change of the ventricle alone (.7 c.c.), as recorded by a cardiometer connected with a tambour, are far greater than those of the whole heart (.2 c.c.)

SUMMARY (Cont.)

5.   Volume changes of the dog's heart recorded using the
pericardium as a cardiometer show that during systole
the volume of the heart decreases, and before systole has
ended, it increases to a varying degree depending upon
the rate and venous pressure. This increase is due to
the filling of the auricles, and this filling proceeds to
a much greater extent during ventricular systole than
previously supposed.

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<div align="right">John H.Rompf</div>