Instantaneous Dimensional Changes of the Left Ventricle in Dogs

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The most meaningful way of determining the mechanisms operative in the moment-to-moment control of ventricular functions is to obtain an accurate estimate of the performance of the heart in intact, unanesthetized animals. For this purpose, we should monitor exactly both static and dynamic cardiac effort. The important factor to be followed, therefore, is that of total cardiac work, both in normal, intact animals and in animals under a variety of circumstances. An estimate of the total tension developed by the heart is required when trying to follow the work from moment to moment. As has been previously stated, "the total tension developed by the heart can be accurately calculated when one knows the systolic residual and the end-diastolic volumes, the end-systolic and end-diastolic intracavitary pressures, the rate of change of volume and pressure from moment to moment during the contraction of the heart, and the K value of Laplace's Equation."1

Our own studies have evolved from an attempt to monitor the instantaneous changes in the external volume of the left ventricle in intact, unanesthetized dogs by a technique of electromagnetic plethysmography. This method permits the continuous recording of the summated external cross-sectional areas of the left ventricle. The external volume of a chamber, such as the left ventricle, is directly related to, and varies with, the mean cross-sectional area of the chamber times its length. Where the changes in length of this chamber are extremely small, the instantaneous volume will be directly related to the sum of a series of its simultaneously and instantaneously recorded sequential cross-sectional areas. The accuracy to which this volume may be recorded depends solely on the number of such sequential areas recorded and added together. An infinite number of infinitely thin segments is the limit and represents the total volume. In order to assess the merits of using measurements of cross-sectional area alone to monitor changes in left ventricular volume, one must first compare left ventricular length and cross-sectional area simultaneously. Studies of instantaneous dimensional changes of the left ventricle in intact animals have been made by Rushmer and his colleagues.4-18 The dimensional changes most studied by them were diameter, circumference, and length, but it still remains to be seen how far these dimensions actually reflect changes in left ventricular volume.

The purposes of this paper are: (1) to describe and compare the instantaneous dimensional changes of left ventricular length and cross-sectional area in connection with changes in pressure in both the intact and the open-chest, anesthetized dog; (2) to point out the more correct pattern of instantaneous changes in left ventricular length; and (3) to suggest that both length and cross-sectional area need to be followed in estimating instantaneous volume changes of the left ventricle.

Methods

Measurement of Left Ventricular Length

Left ventricular length in open- and closed-chest dogs was recorded by means of a variable resistance gauge consisting of delicate rubber tubing (0.015 in. I.D. and 0.044 in. O.D.). In preparing a gauge, the tube is filled with Hg and sealed at both ends with tapered rubber or silver pins to which are attached insulated wires. These gauges are similar to those employed by Whitney10 for limb plethysmography and by Rushmer20 for monitoring left ventricular length and circum-

*Available from Huntington Rubber Mills, Box 570, Portland, Oregon.
The linearity and response time of the gauges were found to be as previously reported by Rushmer, and Lawton and Collins. Left ventricular length was monitored by utilizing a calibrated gauge to the external surface of the ventricle wall. The gauge was fastened to the wall under slight tension (equivalent to approximately 0.5 Gm. or less) on a line parallel to the interventricular septum and from a point just below the atrioventricular valve ring to the apex. Securing sutures were placed through the full thickness of the ventricular wall. This latter was the major difference in application from that of Rushmer. The recordings of length obtained in this manner were qualitatively the same as those obtained by use of a strain gauge caliper (fig. 1).

Measurement of Cross-Sectional Area

The method for measuring cross-sectional area utilizes the fact that an electrically conductive closed loop, when placed in an alternating magnetic field of homogeneous density, has induced in it an electromotive force (EMF), which is a function of the cross-sectional area of the projection of the loop on a plane normal to the direction of the magnetic flux. By attaching either a corrugated, pliable wire or a conductive loop (consisting of Hg in thin rubber tubing sealed at both ends with tapered steel or silver pins to which are attached insulated wires) around an organ surface to form a closed loop, and by introducing the organ and its loop into a uniform alternating magnetic field perpendicular to the plane of the loop, an alternating voltage is produced at the ends of the leads; this is proportional to the area enclosed by the loop and independent of its shape and circumference. A system of tuned amplification, filtering, rectification, and recording of this voltage has demonstrated the practicability of the theory.

For the present studies, the cross-sectional area was monitored from a single segment about the middle of the left ventricle on a plane normal to its long axis. This was accomplished by placing the awake dog in the recumbent position within the cage in such a way that the plane normal to the windings was horizontal. The total length of the coil thus produced was approximately 5 feet and the distance between the loops was approximately 4 inches. The recording table was 4 feet below the atrioventricular valve ring to the apex. During a recording session the intact, unanesthetized dog was placed on the table on his right side and rotated along the horizontal axis until the maximum output voltage from the closed, elastic, and conductive loop about the left ventricle was obtained. A typical recording secured under these circumstances also appears in figure 1. The coil about the frame was energized with an A.C. current of approximately 0.5 volts and 40 watts, through a total resistance of 4 ohms. The current was supplied by a MacIntosh power amplifier, driven by a Dumont oscillator, usually at a frequency of 10,000 c.p.s. This produced within the loop a homogeneous magnetic field. For the purposes of testing homogeneity as well as calibration, a square closed “standard” loop was used which could be adjusted at will in terms of its cross-sectional area. By means of this standard loop, it was discovered that the field produced was truly homogeneous and that changes in induced voltage were linearly proportional to changes in cross-sectional area. The output voltage from the elastic loop is carried from the dog to a general radio null detector and amplifier with a tunable filter. The amplified output is rectified, filtered, and then passed to a Sanborn D.C. preamplifier with zero suppression.

Measurement of Circumference

Aortic circumference (fig. 1) was measured by use of a variable resistance gauge snugly secured about the root of the ascending aorta, just above the origin of the coronary arteries. Left ventricular circumference was recorded, using the technique described by Rushmer. While calibration of the aortic and ventricular circumference gauges was possible, and used when desired, in this report only the qualitative circumference is discussed.

In the awake, intact dogs aortic circumference was usually monitored for timing of events during the cardiac cycle in preference to aortic pressure, since the former was easier to follow from day to day while the dogs were in their cages.
A typical relation between aortic pressure, as measured at the level of the circumference gauge, and the changes in aortic circumference was found in preliminary studies. An increase in aortic circumference preceded a rise in aortic pressure, and x-y plots of the relationship between the instantaneous changes in aortic pressure and circumference produced a linear counterclockwise loop, similar to those previously described by others. 

**Measurement of Pressure**

The zero reference point for calibration of the pressure transducers was always the level of the left atrium of the dog. Aortic pressure was measured by use of a large-bore (2 mm. I.D.) brass cannula, 14 cm. in length, connected through a short segment (6 in.) of lead tubing to either a Sanborn differential pressure transducer (model 267B) or a Statham strain gauge (model P23AA). The gauges were connected to a Sanborn carrier preamplifier.

Ventricular pressure and left atrial pressure were recorded through Sanborn differential pressure gauges (model 267B). In the intact dog, the technique described by Rushmer was used for recording effective ventricular pressures. Essentially, the ventricular pressure was recorded by passing a short polyethylene tube through the atrial cannula into the ventricle and connecting this through lead tubing to the P1 side of the differential manometer and connecting the polyethylene balloon through its attached tubing to the P2 side of the manometer.

The standard limb leads were recorded, and usually lead II was used for electrocardiographic tracings.

Over 60 dogs were used. In open-chest studies, a standard left thoracotomy was performed. Ventricular pressure was recorded by means of a short metallic cannula secured in the apex of the ventricle. A long, curved, 15-gauge syringe needle was most effective in placing the rubber gauges about the left ventricle. It was passed through the right ventricle close to the ventricular septum about the middle of the heart when one coil was used. It served as a guide for the lead-off wire from the mercury-in-rubber gauge. When the needle was withdrawn, the wire was led through the right heart and the rubber gauge could be pulled through with ease and secured. The rubber gauge was then attached by fine suture at several points to the ventricle, so that the plane of the closed loop formed was normal to the long axis of the heart. This was checked by direct vision and in the earlier dogs by x-ray. Sodium pentobarbital (30 mg./Kg. of body weight, given intraperitoneally) was used as the anesthetic, and in long studies of 12 to 14 hours, supplemental doses were given by vein, as needed. In open-chest dogs, artificial respiration was used, usually with 100 per cent oxygen. In the chronic dogs, sterile surgery was performed, and the animals were permitted to awaken. Recordings were made on a Sanborn eight-channel polyviso simultaneously in the chronic dog, immediately postoperatively and at irregular intervals thereafter (for periods exceeding five months in some dogs) until either the gauges broke or the dog was killed.

**Results**

**Left Ventricular Dimensional Changes in Anesthetized, Open-Chest Dogs**

Figure 3 shows the typical qualitative changes in aortic pressure, ventricular pressure, ventricular cross-sectional area, base-to-apex length, and lead II of the electrocardiogram, as simultaneously recorded in open-chest dogs. Figure 3 is a direct tracing of a record as simultaneously recorded on Sanborn eight-channel recording paper. More than 30 dogs, weighing 14 to 16 Kgs., were studied in this manner. Base-to-apex length of the left ventricle varied between 6 and 8 cm. The total recorded change in base-to-apex length varied from 5 to 7 mm. during a particular cycle. These recorded changes in base-to-apex length were made by using the variable resistance length gauge. Figure 3 has been divided into three sections as indicated by the lines of Ro-
man numerals (I, II, III, and IV). Isovolmic contraction (I to II) is indicated by the observation that there is shortening of the base-to-apex length with a concomitant increase in cross-sectional area during the time when the ventricular pressure is rising and the aortic valves have not yet opened. The ejection phase (II to III) is characterized dimensionally by a minimal change in base-to-apex length (less than $\frac{1}{2}$ mm.) and a continuing reduction in cross-sectional area. The periods of rapid filling, diastasis, and atrial systole are encompassed between (III) and (IV). Clear separation of these three periods is difficult. At the onset of incisura (III), ventricular pressure begins to decrease, while the base-to-apex length begins to increase sharply. During the period of sudden decrease in ventricular pressure, oscillographic x-y plots of the relation between changes in ventricular pressure and base-to-apex length indicate that there is a direct linear relation between these two parameters. An increase in cross-sectional area begins after the base-to-apex length has increased to a maximum. Atrial contraction is not clearly defined by the dimensional changes recorded. An indication of a decrease in base-to-apex length during this period is suggested on the tracing.

The qualitative appearance of the dimensional changes in open-chest dogs is different from those seen in unanesthetized animals.

The differences are in the finer details of the changes occurring during atrial contraction, initial systolic expansion of cross-sectional area, rapid filling, and diastasis. The initial systolic expansion of cross-sectional area is more obvious in some anesthetized dogs than others. Figure 3 represents the average change during this period.

The changes in base-to-apex length are significantly greater in the left ventricle of the open-chest dog (6 to 8 mm.) during a cardiac cycle than in the awake intact dog (2 mm.). This is true even though the open-chest dog has a smaller heart than the awake, intact dog. The latter has been observed previously in our laboratory and in the laboratory of Rushmer. In open-chest dogs the major length changes of the ventricle occur during the periods of isovolumic contraction and relaxation. During ejection, the major change is a decrease in cross-sectional area.
Left Ventricular Dimensional Changes in Awake, Intact Dogs

Changes in Base-to-Apex Length

Figure 4 is a tracing from a simultaneous recording of aortic circumference, effective left ventricular pressure, and base-to-apex length in an awake dog, six days after operation. Shortening of base-to-apex length during a cardiac cycle was usually 3 mm. in this dog. The total base-to-apex length was 7 cm. at the time of operation. The major shortening of base-to-apex length occurred during the period (I to II) of initial rise in ventricular pressure prior to opening of the semilunar valves, indicating that there was a period of isovolumic contraction. During the ejection period (II to III), base-to-apex length varied from a minimum of 0.2 mm. to a maximum of 1 mm. in different dogs on different days after operation (6 to 28 days). In this dog (fig. 4), the lengthening approximated 1 mm. At the incisura, base-to-apex length started to increase sharply toward its maximum for that cardiac cycle. This increase occurred during the time when ventricular pressure was falling and, at first, was above the pressure in the left atrium. During diastasis (IV to V), practically no change in length was seen. Atrial systole was clearly marked by a shortening, followed by elongation of the length gauge.

Changes in Cross-Sectional Area

Figure 5 shows the typical pattern of changes in cross-sectional area as seen from the sixth postoperative day forward. In the first two to four days after operation, the form of the cross-sectional area tracing gradually changes from that typically found in the open-chest dog to the one presented in figure 5. The form of this area change is strikingly similar to that found where recordings of circumference are made (fig. 7). In figure 5, the phases of the cardiac cycle are found between the lines marked (I) to (VI). The tracing was made at a paper speed of 100 mm/sec., and aortic circumference was monitored simultaneously for timing purposes. Period (I) to (II) shows the phase of atrial contraction; (II) to (III), isovolumic contraction; (III) to (IV), ejection; (IV) to (V), rapid filling; and (V) to (VI), diastasis.

Calibration of the closed conductive loop about the middle of the left ventricle in terms of area, though routinely made, is not shown in figure 5. This report is concerned primarily with the qualitative instantaneous changes in this dimension during the cardiac cycle. Our studies have shown, however, that in dogs of approximately 14 Kg. of body weight, the average end-diastolic cross-sectional area about the middle of the ventricle was approximately 19 sq. cm., while the dog was resting quietly; the average end-systolic value approximated 15.4 sq. cm.

Figure 6 shows the simultaneous recording.
of length and area, along with aortic circum-
ference and lead II of the electrocardiogram
in a dog 21 days after operation. The total
shortening base-to-apex length during iso-
volumic contraction was approximately 1 mm.
This is in striking contrast to open-chest dogs
in which total shortening varied between 6
and 8 mm. during this period. During ejection
(III to IV), an elongation (approximately
0.7 mm.) in base-to-apex length is seen. Rapid
filling is suggested as occurring between (IV)
and (V); however, it is more likely that this
occurs between (IVa) and (V) and that the
period between (IV) and (IVa), during
which lengthening of the ventricle is seen,
represents isovolumic relaxation.

Simultaneous Changes in Left Ventricular Cross-
Sectional Area and Circumference

To determine the instantaneous changes in
the circumference and cross-sectional area
about the same plane of the left ventricle,
two variable resistance gauges were used.
These gauges were placed parallel to each
other about the middle of the left ventricle
on a plane normal to the long axis of the
ventricle, so that the closed loops thus formed
were within 2 mm. of each other.

When ventricular circumference was re-
corded from each of these two loops simul-
taneously, an x-y plot showed a linear relation
between the circumference changes indicated
independently by the two loops. This finding
indicated that they were monitoring the di-
mensional changes of an identical segment
about the middle of the left ventricle.

Figure 7 records the relationship between
the instantaneous changes of area and cir-
mumference about the left ventricle in a
typical intact, awake dog. The x-y plot in
figure 7 has a long linear portion which
approximates 45 degrees. This portion of the
tracing represents the relation between cir-
mumference and area during the ejection phase
of the cardiac cycle. This finding indicates
that the left ventricle contracts in an eccentric
manner. Figure 8 summarizes, in a diagram-
matic fashion, our belief as to the external
dimensional changes of the left ventricle in
awake dogs during a cardiac cycle.

Discussion

Left Ventricular Dimensional Changes in Awake
Dogs During the Cardiac Cycle

Base-to-apex length, as described in this
paper, is to be distinguished from the length
changes of the left ventricle as recorded and
reported by others.20, 25,27 One of our sig-
nificant findings is that there is shortening
of the ventricle during the period which has
classically been labeled "isometric" contrac-
tion. This observation is in keeping with the
findings of Wiggers23 and Rushmer.24 This
period should be referred to as isovolumic.
Rushmer,20 using Hg in rubber gauges for
length measurements, attached his gauges
under slight tension to the superficial muscles
(superficial sinospirals) and recorded, not an
index of the length of the ventricle, but
rather changes in length of these superficial
fibers. He also has recorded length changes
internally.25 These recordings more nearly
approximate those we observed by using the
external length gauge, as we applied it. Linden
and Mitchell26 recorded changes in myocardial
segment length, but the length of the segment
they studied was usually 25 mm., whereas
the average total base-to-apex length of the
dog heart approximates 5 to 8 cm. It should
not be expected, therefore, that this segment-
length measurement would record changes in
base-to-apex length. Changes in segment length,
as recorded by these investigators, did not
always show an initial shortening during the
isovolumic period of contraction, but did
show routinely continuing shortening through-
out the ejection period. The strain gauge
of Cotton\textsuperscript{27} seems to measure changes in iso-
metric tension of a small segment of stretched
myocardium. Recordings made with this gauge
show increases in tension starting with the
beginning of the isovolumic period of con-
traction. For approximations of volume, it
is essential to differentiate the total length
of the ventricle from changes in length of its
superficial muscles and various segments of
the total length. This is important since an
instantaneous external volume approximation
should be a function of the product of the
total base-to-apex length and the mean cross-
sectional area of the ventricle.

The initial change in length of the ventricle
reflects primarily the changes in lengths of
the shortening fibers which lie in the plane
parallel to the length gauge. Dissection of
the left ventricle in dogs shows these fibers
to be the deep sinospiral muscles. It has
been previously suggested that the deep
sinospirals contract first\textsuperscript{24, 28–30} and conse-
quently the trabeculae carneae and papillary
muscles may be the only left ventricular
muscles shortening during the phase of iso-
volumic contraction. Our studies suggest that
work is done by the left ventricle in raising
its intraventricular pressure to that present
in the aorta just prior to ejection, and that
this work is accomplished primarily by con-
traction of the deep sinospiral muscles. The
possibility that changes in coronary flow and
wall thickness of the left ventricle during
isovolumic contraction may contribute arti-
facts to the base-to-apex length recording has
been considered. In view of the similarity
of our recordings to those of Rushmer, made
inside the ventricle, and our finding that the
use of the strain gauge caliper in open-chest
dogs records length changes identical to those
from the variable resistance length gauge
(when the latter is attached to the ventricle
wall by through-and-through sutures), we are
inclined to dismiss the above possibility during
this phase of contraction. In two experiments,
not reported here, we have passed a length
gauge through the ventricular cavity from
apex to base and recorded tracings of length
changes similar to those obtained from the
surface length gauge.

Our studies show that immediately at the
end of ejection there is a sudden increase in
base-to-apex length. This increase begins in
the awake, intact dog prior to a noticeable
change in cross-sectional area in the ventricle
and during a time when the ventricular pres-
sure is above the left atrial pressure. The
decision to call this a period of isovolumic
relaxation is made difficult by the lack of a
counter change in cross-sectional area. If
one considers that no change in the volume
of blood in the ventricle occurs during this
period, a change in shape in one dimension
must be coincident with a change in the
other. It has been suggested by Dr. L. N.
Katz that perhaps this period represents a
time when there is a sudden increase in coro-
nary blood flow. It seems possible to explain
in this way our data during isovolumic relaxa-
tion. If coronary flow in early diastole (1) in-
creases wall thickness, on the one hand, and
(2) causes elongation from base to apex as
well as decrease of the cross-sectional area, on the other, then the following would happen: the effect of (1) and (2) would summate as far as length is concerned, while the effect of (1) and (2) would neutralize each other as far as cross-sectional area is concerned. Further studies are needed on this period to clearly define its significance.

The sudden decrease in length of the ventricle and a simultaneous increase in cross-sectional area during the period of atrial contraction points to the fact that a change in shape of the ventricle is occurring. This observation shows that one must be careful in drawing conclusions about changes in the atrial contribution to ventricular volume when monitoring a single left ventricular dimension.

Changes in Left Ventricular Cross-Sectional Area

The instantaneous changes in cross-sectional area about the middle of the left ventricle in the awake dog are similar to those changes recorded in circumference. The three outstanding qualitative features of cross-sectional area recordings in awake dogs are: (1) significant size of the atrial component; (2) the increase in area during isovolumic contraction; and (3) the changing nature of the length of diastasis. The atrial component of area tracings indicates a contribution to the volume of the ventricle by atrial contraction amounting to 30 to 40 per cent of its end-diastolic size. While a similar suggestion is seen from measurements of circumference about the middle of the ventricle, diameter gauges record little change during this period. Tracings of left ventricular diameter do not show a significant atrial component. This may be due to the fact that the maximum diameter about a plane through the middle of the heart shifts its axis during the period of contraction and relaxation as a result of the change in shape of the segment. The initial systolic expansion of the cross-sectional area confirms the finding that the major decrease in base-to-apex length of the ventricle occurs during the period of isovolumic contraction. During diastasis, in awake dogs, there is no change in cross-sectional area, and the length of the period increases and decreases with the heart rate.

Since during the ejection phase of each cardiac cycle the major external dimensional change of the left ventricle is a decrease in cross-sectional area, we feel that the magnitude of this change may be used as an index of stroke volume.

Relation Between Left Ventricular Cross-Sectional Area and Circumference

It is significant that an x-y plot of the instantaneous changes in area and circumference about the middle of the left ventricle shows an approximately straight line, 45 degrees to the abscissa. This finding suggests a continuing change in shape of the left ventricle during ejection and makes difficult the interpretation of changes in left ventricular diameter or circumference in relation to volume. It would appear that for diameter and circumference to accurately reflect volume changes, the ventricle should decrease in size and increase in size concentrically. If the middle portion of the left ventricle were decreas

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Figure 8

Schematic diagram indicating the shape of the left ventricle at the end of each phase of the cardiac cycle. The arrows indicate changes in length and diameter. End of diastole (I); end of isovolumic contraction (II); end of ejection (III); end of rapid filling (IV); end of diastasis (V); end of atrial systole (VI).
ing concentrically in size in a plane normal to its long axis, mathematical analysis shows that the x-y plot of area and circumference would, of necessity, show a curvilinear relationship, and the curve so formed would be convex to the abscissa. The changes in shape mean that the maximum radius of the ventricle is constantly shifting in a plane normal to the long axis of the ventricle. It may be assumed that during ejection the ventricle tends to become elliptical, and during filling it becomes more circular. This is an attractive hypothesis, especially since the plane of the deep bulbo-spiral muscles is oblique to the long axis of the ventricle and, as such, contracts along a plane which must be ellipsoidal in shape. The degree of departure from a circular shape of the segment, at any given circumference, then represents loss of area available for blood to remain after the decrease in area has been accomplished.

A study of the relation between the change in area and circumference can thus be used as an index of efficiency of contraction of the left ventricle.

Summary

The cardiac cycle in dogs starts with an isovolumic period in which there is shortening of the base-to-apex length with an increase in cross-sectional area. Total shortening is about one-fourth of that in open-chest dogs. Minimal changes in base-to-apex length occur during the ejection phase, and there is a typical pattern of decrease in cross-sectional area. During isovolumic relaxation, the left ventricular base-to-apex length increases. Rapid filling is characterized by a sudden increase in cross-sectional area and is followed by a diastasis of varying lengths. Atrial systole is associated with a sudden significant increase in cross-sectional area and a decrease in base-to-apex length. The magnitude of change in cross-sectional area about the left ventricle during ejection may be used as an index of stroke volume. Our studies suggest that the ventricle contracts in an "eccentric manner," and relaxes in a "concentric fashion." Simultaneous monitoring of the instantaneous changes in cross-sectional area and circumference about the middle of the left ventricle may be used as an index of its efficiency of contraction in awake, intact dogs.

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