Length-Circumference Relations of the Left Ventricle

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Changes in length and circumference of the left ventricle were recorded simultaneously by variable resistance gages on its external surface in intact dogs. The absolute changes in circumference were considerably greater than the changes in length, but the relative changes in these dimensions were similar (averaging around 2 to 3 per cent). Under most circumstances, the length and circumference vary in the same direction but occasionally inexplicable differences in response were observed.

According to traditional concepts, the ventricles eject blood primarily by shortening of the longitudinal axis, accompanied by a rotational movement which has been compared to "wringing out a wet rag." These views were based largely on anatomic dissections and direct observation of exposed beating hearts. Direct measurements of the changing ventricular dimensions in intact animals by cinefluorographic techniques and by intraventricular gages indicated that left ventricular contraction is characterized by a reduction in transverse diameter, with relatively slight shortening or rotation. The orientation of the myocardial bundles suggests that the superficial spiral muscles probably act primarily to diminish the length of the left ventricle and the thick cuff of circumferentially-arranged fibers reduce its diameter and circumference. An accurate description of left ventricular function requires information concerning the relative contributions of these changes in chamber dimensions. In view of the discrepancies between observations on excised or exposed hearts and the measurements on intact animals, left ventricular length and circumference have been recorded simultaneously in intact, unanesthetized dogs.

Methods

Left ventricular length and circumference were recorded by variable resistance gages consisting of delicate rubber tubing (0.016" I.D. and 0.030" O.D.) filled with mercury and sealed at each end with insulated wires. These gages are similar to those employed by Whitney for plethysmography. Elongation of the gage reduces the cross-sectional area and increases the length of the mercury column, producing a corresponding increase in electric resistance. The gage formed one leg of a Wheatstone bridge, activated by the carrier wave of a Sanborn strain gage amplifier, and its output was recorded on a Polyviso. The linearity and response time of representative gages are illustrated in figure 1. Elongation of the gages required 1.6 to 1.8 Cm. per mm. stretch. The electric resistance of the mercury column was about 0.5 to 0.6 ohms and increased by about 0.02 ohms per mm. stretch. By fastening one end of such gages to a motor-driven eccentric, repetitive stretch for periods of 1 or 2 weeks produced no change in calibration. When gage failure occurred, an open circuit was produced due to entrance of air or leakage of mercury through the wall of the tubing.

Ventricular length was recorded by applying a calibrated gage to the external surface of the left ventricular wall. With the gage under slight tension, the two ends were fastened by sutures at the apex and at a point just below the atrioventricular valve ring. Left ventricular circumference was recorded from a gage which encircled the left ventricle, following the interventricular septum within the right ventricular cavity (fig. 2A).

Heart rate was monitored continuously by a condenser discharge triggered by the change in circumference. The voltage drop during each cycle was directly related to the cycle length which could be calibrated as heart rate by means of an external
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Fig. 1. The increase in resistance of the Hg column in the gage is uniform for each unit of elongation over a range up to 100 per cent of the relaxed length above which the resistance per unit stretch progressively diminishes. The response is nonlinear during the initial stretch of about 1 mm. ordinate: gage resistance (ohms); abscissa: gage length (cm.).

oscillator. After an abrupt change in rate, it required approximately three cycles to reach the new level. Thus, the heart rate was reliably indicated during gradual changes but not during sudden changes in cycle length as occur with premature contractions.

The gages were installed in 11 dogs under aseptic surgical conditions. The insulated wires were led to the outside through the posterior thoracic wall and the incision closed. On the day of operation, records were obtained during responses to epinephrine, acetylcholine and pneumothorax, while the animals were still anesthetized. After recovery from the operation, records were obtained during spontaneous activity such as changes in position, eating, startle and exercise. In most of the animals, at least one of the gages failed during the first week due to the stress of the repetitive stretch, but in one animal, both gages functioned reliably until the animal was sacrificed 19 days after the operation.

Roentgenograms, exposed along the longitudinal axis of the heart (60 degrees from the longitudinal axis of the body) demonstrated that in general the circumference gages described a circle except for slight flattening over the interventricular septum. The circumference of the circle described by the gage was measured on these films.

RESULTS

The recorded patterns produced by alterations in left ventricular length and circumference during cardiac cycles were generally very similar (fig. 2B). The magnitude of the change in circumference was invariably larger than the change in external length, ranging around 5:1 but extending from 15:1 to 2:1. The change in circumference was rarely greater than 0.6 to 0.7 cm. from an average circumference of 15.5 cm. Thus, the extent of myocardial shortening was an ex-
Lift ventricular circumference
AIR INJECTED & REMOVED

PNEUMOTHORAX PRODUCED
PNEUMOTHORAX ELIMINATED

FIG. 3. Typical effect of pneumothorax on left ventricular circumference, length and rate.
The initial increment of air (50 cc.) produced a noticeable irregularity in heart rate and slight reduction in both diastolic and systolic dimensions. While the 500 cc. of air remained within the thorax, the length and circumference progressively increased and the heart rate slowed. The diastolic circumference exceeded the recording range on the paper. There was little change in the variables during the withdrawal of the air but, after the pneumothorax was eliminated, the circumference and length expanded further and the heart rate slowed even more.

tremendously small proportion of the external circumference. The total length of the ventricle was around 5 cm. and the change in length was usually of the order of 0.1 cm. or less.

Comparison of roentgenograms exposed before and during the operation often revealed a striking reduction in the size of the cardiac silhouette which has been previously described in anesthetized, thoracotomized animals. Since this “shrinkage” of the heart might result from pulmonary atelectasis, changes in left ventricular dimensions were routinely recorded during an experimentally induced pneumothorax one or two hours after the surgery was completed. For this purpose a rubber tube leading from the thorax to the outside was routinely installed during closure of the wall. Through this tube, a total of 300 to 500 cc. of air was injected into the thorax in 50 cc. increments. After a brief period, the air was again removed. The typical response to this procedure is illustrated in figure 3. While the air was injected, left ventricular circumference and length diminished slightly, the heart rate diminished slightly at first and then accelerated a few beats per minute. While the pneumothorax was maintained, the heart rate diminished as both left ventricular dimensions increased and respiratory activity became greatly intensified. The increase in systolic and diastolic dimensions, stroke excursions and slowed heart rate persisted during and after the withdrawal of the air.

In these animals, pneumothorax consistently produced an increase in left ventricular dimensions and could not be solely responsible for the shrinkage of the heart which generally accompanies thoracotomy. However, there was a close temporal relationship between heart rate and changes in left ventricular size. Thus, tachycardia might play a significant role in reducing the heart size during intrathoracic or cardiac surgery. The cause of the cardiac slowing associated with pneumothorax was not clear but neural reflexes are presumably involved.

The ventricular response to intravenous injection of a standard dose of adrenalin (.003 mg./Kg.) varied in different animals and in the same animal under different conditions. A typical response is illustrated by dog 33 at the top of figure 4. The initial response was a transient increase in both circumference and length, followed by tachycardia and diminution...
of both systolic and diastolic dimensions. As
the heart rate slowed below the control levels,
the left ventricle expanded. Rather large
fluctuations in the stroke amplitude and heart
rate were apparently due to forced respiratory
efforts. The responses in the other anesthetized
animals were comparable in most respects. The
changes in length and circumference were
usually in the same direction throughout.
However, the response of dog 30 (fig. 4) is
presented to illustrate an exceptional circumstance
in which the changes in left ventricular length
were quite different from the changes in cir-
cumference. In this case the principal changes
were a marked increase in diastolic length,
while the circumference was diminished during
both diastole and systole. Records from this
animal under other conditions did not exhibit
such a discrepancy in the response by the two
dimensions of the ventricle. The effects of
epinephrine on the intact conscious animal are
illustrated by a record obtained 19 days after
the operation (fig. 4). The latency of the
response was considerably reduced and the
most significant effect was bradycardia which
was more severe and more persistent than that
observed in the same and in other animals
under anesthesia. This difference may be due to
parasympatholytic effects of Nembutal.
Eating produced a pronounced acceleration
of the heart rate accompanied by an increase
in both diastolic and systolic dimensions of the

Fig. 4. Variable effect of adrenalin administered intravenously during the interval indicated by
the two vertical arrows.

The primary effects of adrenalin on the left ventricle were obscured by peripheral vascular effects
and reflex activity. Discussion in text.
ventricle. The response began immediately after the food was presented and persisted throughout the feeding period. In one animal, the typical response was obtained during eating. The empty plate was removed some distance and placed in front of him again. Although the animal watched the entire procedure, the empty plate initiated a very similar but transient response by the heart even though the animal did not appear to evidence interest in the plate.

The cardiac response to exercise was recorded from two different animals. In the first instance, the principal change during exercise was an increase in both diastolic circumference and length. On other occasions, this same animal exhibited greater systolic ejection with lesser degrees of diastolic expansion of the left ventricle. In the second animal, diastolic circumference increased predominately and systolic circumference decreased somewhat. At the same time, the principal change in length was greater systolic reduction with little change in diastolic length. In other words, the predominant changes in length and circumference were in opposite directions in this particular example.

DISCUSSION

The changes in circumference during the cardiac cycles, ranged around 0.5 cm. with an average total circumference of 15.5 cm. The length was usually diminished 0.1 cm. or less from a total length of about 5 cm. However, the relative contributions of these changes in dimensions to the ejection of blood depends upon the size and geometrical configuration of the left ventricle. Consider a cylinder with a circumference of 15.5 cm. and a length of 5 cm. With the length unchanged, reducing the circumference by 0.5 cm. would reduce the volume by 6.1 cc. Conversely, reducing the length 1 mm. with the circumference unchanged would diminish the volume by 1.9 cc. The sum of these values (8 cc.) represents a rough approximation of left ventricular ejection. The complex geometric configuration of the left ventricle precludes accurate computation of volume knowing length and circumference, particularly since the exact changes in shape of the chamber are not well established.

During systole, the circumference was reduced by about 3 per cent and the length was diminished by about 2 per cent. This indicates that the superficial myocardial layers shorten by a small proportion of their total length. The inner layers of myocardial fibers must shorten to a greater extent than the external layers. Previous measurements indicated that the internal diameter of the left ventricular chamber is reduced by about 0.5 cm. from a total of 2.7 cm. or a relative shortening of about 12 per cent of diastolic dimension. The relatively small degree of myocardial shortening indicated by these measurements has important functional significance. Judging from studies of myocardial strips by Lundin, contractile tension, developed during isometric contraction, falls precipitously if the muscle is permitted to shorten rapidly during contraction. The loss of tension during contraction is related to the rate and degree of shortening. Thus, the myocardium maintains a higher contractile tension if the degree of shortening is small. Furthermore, the contractile energy stored as tension between muscle bundles (interfascicular tension) is presumably diminished by smaller degrees of myocardial shortening. A particular stroke volume can be ejected with such slight myocardial shortening only if the end diastolic volume is large. Thus, the ventricles function more efficiently at large diastolic dimensions so that large volumes of blood remain within the chambers at the end of systole.

Occasionally the length and circumference did not change in the same direction. These examples occurred as exceptional incidents in preparations which were otherwise functioning consistently and well. There was no reason to suspect that they were due to instrumental artifacts. It is worth noting that the changes in length are produced primarily by the superficial spiral muscles on the external and internal surfaces of the walls. The changes in circumference are produced predominately by the deep circumferential muscle bundles. These two sets of muscles apparently did not respond in precisely the same way on certain occasions.
Simultaneous recordings of the external length and circumference of the left ventricle in intact dogs generally exhibited similar patterns during cardiac cycles.

Left ventricular length usually diminished less than 0.1 cm. from an initial length of about 5 cm. (0.02 per cent). The circumference diminished about 0.5 cm. of a total of 15.5 cm. (0.03 per cent).

In a cylinder 5 cm. long and 15.5 cm. in diameter, shortening by 1 mm. would reduce its volume by 1.9 cc. and reducing the circumference by 0.5 cm. would diminish its contents by 6.1 cc.

Left ventricular length and circumference characteristically varied in the same directions during responses to epinephrine, acetylcholine, pneumothorax and spontaneous activity, including changes in position, eating and exercise. A few examples are presented indicating that the changes in length may be quite different from the changes in circumference.

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