Intramural Myocardial Shear During the Cardiac Cycle

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Study of the heart's geometry throughout the cardiac cycle is necessary if a precise description of myocardial function is to be developed. The problem has been attacked using cinefluorographic techniques and by using transducers designed to measure dimensions of the heart continuously. If such measurements are to be interpreted uniquely in terms of muscle fiber shortening for the entire heart, it is necessary to determine the relationship between the magnitudes and directions of muscle shortening in the various layers of the wall. To the extent that the various layers are contracting differently, a shearing strain will occur in the wall during contraction. It is the purpose of this report to present measurements of shear that occur in the wall of the myocardium in vivo.

Methods

A transducer has been devised to measure the shear of the myocardium at various depths as illustrated in figure 1. In principle the device consists of an exploring probe designed to measure angular displacement. A pivoted shaft with a small triangular blade at its end was used to cut a small slit in the myocardium, and then was turned so that the corners of the blade engaged the adjacent heart muscle. The angular displacement of the blade with respect to the epicardial surface was used as a measurement of angular strain or shear. In detail, the movable shaft, A, is held in a sleeve, B, which is mounted on an axis, C, perpendicular to shaft A. This allows rotation in a single plane about the axis C. The rotation about the C axis produces a displacement of the end of shim, D. This thin brass shim undergoes small bending strains with this displacement. Two small etched foil strain gauges are bonded on the shim and form two arms of a resistance bridge. The changes in the bridge resistance which result from the bending of the shim are sensed and suitably amplified with a standard carrier amplifier to give a varying voltage signal which can be recorded. The transducer is attached to the heart with shallow sutures threaded through the corner holes in plate, E. At the end of the shaft, A, there is a small flat triangular blade, F, which cuts a fine slit in the muscle when the movable shaft is thrust into the myocardium. This slit is cut perpendicular to the C axis. The blade is then turned 90 degrees so that the two side corners of the triangular blade hook into the wall of the slit in the muscle. The shaft is thus free to swing in the slit but fixed to the myocardium by the corners of the blade at the end of the shaft. The angular movements of the shaft can be recorded when it is inserted at various depths into the myocardium. This angle is called "shear" in this study and represents the average of shears between the epicardial surface and the corners of the blade.

The efficiency of coupling between the gauge and the myocardium was tested by shearing a freshly excised piece of heart muscle, a known...
amount, between two emory surfaced plates. The shear gauge reading was from 94% to 98% of the calibrating shear.

The transducer was calibrated before and after each run with a small test stand, utilizing a micrometer to rotate the shaft known distances. The transducer was essentially linear through the ranges encountered. A static calibration curve is given in the left side of figure 2. The dynamic frequency response of the instrument is shown in the right side of figure 2.

Large dogs were anesthetized with chloralose (60 mg/kg) and urethane (600 mg/kg) after morphine (2 mg/kg) preanesthetic. The left aspect of the heart was exposed with a sternal splitting incision and partial resection of four to six left ribs. Aortic arch pressure was recorded through a catheter inserted via the left subclavian artery. Left ventricular pressure was recorded with a cannula through an apical myocardial puncture. Pressures were measured with Statham P23d manometers. Instantaneous flow was measured at the root of the aorta just above the valves with a 400 cycles/sec gated sine wave electromagnetic flowmeter. Recording was done on a Sanborn 350 heated pen oscillograph.

The left aspect of the left ventricle was divided into six areas for grouping the data, as shown in figure 3. The shear transducer was placed in one of these areas to measure shear in the direction of the long axis of the left ventricle from base to apex of the heart, or transversely at a right angle to the long axis along the short axis of the left ventricle. Shear was measured at two depths in the myocardium, 3 and 6 mm. The usual procedure was to cut a slit with the blade of the transducer and measure shear during a control period. After this an iv drip of norepinephrine (approximately 0.001 mg/kg per minute) in saline would be started to raise the aortic pressure 10 mm to 20 mm of Hg. A second run would be made during the norepinephrine infusion, and a third after the animal had returned to normal following the infusion.

**Results**

Two hundred and fifteen determinations were made in 80 applications of the shear...
gauge on the left ventricles of 19 dogs. Shear was recorded throughout the entire cardiac cycle, but detailed results will be presented only for the ejection phase of systole. Myocardial motion is probably of most interest physiologically when the heart muscle is shortening and doing active work by ejecting blood from the ventricle. During the beginning and the end of systole the ventricles change shape producing complex shears which will be briefly described.

A representative example of shearing during the cardiac cycle is shown in figure 4. At the beginning of systole, during the “isovolumic” phase of contraction, the heart undergoes a major change in shape as has been described by Rushmer et al. and Hawthorne. In this study relatively large and rapid shearing strains were often observed in the myocardium accompanying this change in geometry. These strains were often five times as great as those during the ejection phase, and sometimes as much as ten times larger. The shears recorded during this period in the cardiac cycle were not of a consistent pattern. Considering the rearrangement of the archi-

FIGURE 4
Simultaneous records of pressures, flow, the ECG, and shear in the wall of the left ventricle. Same parameters to same scale are shown before and during infusion of norepinephrine. Vertical bars on the shear record indicate ejection period as judged from the flow record.
MYOCARDIAL SHEAR

Myocardial shear character of the myocardium occurring during the "isovolumic" period, it is not surprising that relatively large shear strains were found. At the end of systole the ventricle relaxes and again undergoes a major change in geometry. Similarly, during this portion of the cardiac cycle large shears were observed. Shearing during relaxation was in the opposite direction from the shear during the "isovolumic" period. Characteristically the shear during diastole was small.

The period of ejection during systole was determined from the electromagnetic flow recorded at the root of the aorta just above the valves. This interval is indicated by vertical lines on the shear records in figure 4. The degree of shear between the highest and lowest points present in this interval was taken as the shear strain during ejection. The mean value of 80 control determinations of myocardial shear at a depth of 6 mm during the ejection period was 0.0218 radians, ± 0.0026 standard error (1.25 degrees ± 0.15 SE).

Comparisons of the shears at two different depths at the same sites were made in 76 control cases. Shears at a level 3 mm and 6 mm below the surface of the epicardium were measured one after the other. The magnitude of shear during ejection was found to be significantly greater at the lower depth (P < 0.005). The average shear at the 3 mm depth was 0.0120 radians (0.69°), and at the 6 mm depth was 0.0198 radians (1.13°).

The data from the six areas of the surface of the left ventricle were compared to determine if the shear varied from site to site. No significant difference was found in the shears measured from one area of the heart compared to any other.

A statistical comparison was made between the shears measured in the direction of the long axis of the heart, from apex to base, and shears in the transverse direction. No significant difference was found between the magnitude of transverse and longitudinal shears.

The effect of an intravenous infusion of norepinephrine was tested in 58 determinations. The average of two control values (before and after) for the 58 infusions was 0.0177 radians (1.01°). When sufficient norepinephrine was used to elevate the systemic blood pressure 10 to 20 mm Hg, shear increased to an average value of 0.0274 radians (1.57°). This increase was significant (P < 0.001).

Discussion

It is the intent of this study to describe the shearing strains that the ventricular myocardium undergoes while it is actively pumping. It was felt that a characterization of myocardial shear during ejection would be a useful addition to what is known about how the heart contracts. Also it is important to know about the internal movements in the myocardium if one is describing the performance or function of the heart by measuring changes at the surface. A segment length of myocardium measured at the surface, or the entire external circumference of a ventricle, may not be representative of the myocardium as a whole if the various layers of the heart slide over each other. The shears observed during ejection were small. Thus during ejection it is probably reasonable to use a measurement of surface strains to represent the strains in the other layers of the myocardium for many applications. During the periods in the cardiac cycle when the ventricle was changing shape (as in the "isovolumic" phase), shears were much larger and caution should be used in interpreting surface measurements from these periods.

Overall, the variability encountered in the measurements made in this study was too great to demonstrate differences in shear due to position or direction. In an organ as complex as the heart it is quite possible that such differences exist, but they were not demonstrated in these experiments. On the strength of the large number of determinations made in this study, it is probably safe to state that such differences are small.

The shear during ejection was greater at a depth of 6 mm than at 3 mm. This implies that the different muscle layers in the myocardium contract somewhat differently, as might be expected. However, the average difference
between the two depths was small, 0.0078 radians (0.45°).

**Summary**

Instantaneous and continuous shearing strains at various sites in the wall of the left ventricle were measured in 19 dogs with a specially designed transducer. Relatively large shearing strains occurred during the "isovolumic" and immediately prediastolic portions of systole. Shearing strain during diastole was small. Under control conditions the average shearing strain during the ejection period of systole was 0.0218 radians (1.25°) at a 6 mm depth into the myocardium. Intravenous infusion of norepinephrine (approximately 0.001 mg/kg per minute) increased myocardial shear from 0.0177 radians (1.01°) to 0.0274 radians (1.57°) during the ejection period.

It is concluded that shearing strain in the myocardium during the ejection period is relatively small.

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**References**

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