Effects of Alterations in Aortic Impedance on the Performance of the Ventricles


The relationship between the external work done in an isotonic muscular contraction and the load has been extensively investigated for isolated skeletal muscle and, more recently, in isolated strips of heart muscle.1,2 These studies have shown that, for contractions from a constant initial length and tension, the relationships between load and external work or power describe a parabola which is rather more symmetrical for cardiac than for skeletal muscle. Comparable studies relating external work to load have been done on various isolated heart preparations.3-5 In none of these investigations so far has it been possible to define the point or points on the parabola at which the ventricle normally functions.6-8 General conclusions in all these studies have been similar. Nevertheless the applicability of these data to the normal heart remains uncertain. In studies with isolated hearts or in open chest dogs under general anesthesia, ventricular volumes, stroke volumes, and pressures may be abnormal absolutely and relative to each other;6,7 environmental factors like temperature, electrolyte concentrations, and hormonal supply may differ from normal; and the important controls exerted by the autonomic nervous system may be absent or else held at unusual levels. We therefore decided to determine whether the data obtained using isolated hearts and muscle strips were applicable to the left ventricle of conscious dogs and to find out at what point on the curves relating load to external stroke work and power the left ventricle normally functions. At the same time the opportunity was taken to observe the effects on the right ventricle of changing the load on the left ventricle.

Methods

In dogs under general anesthesia, coreless flow transducers were implanted around the roots of the pulmonary artery and aorta.6 After the pericardium was repaired, the transducer leads were brought out through an incision between the scapulas, the thorax was closed, and the dogs allowed to recover. About five days later polyvinyl catheters were permanently implanted through the neck vessels into the ascending aorta and right atrium and were kept patent with heparinized saline. In two animals, at the time of the first operation, a catheter was passed into the left atrium through a small branch of the pulmonary vein. Patency was maintained by filling the catheters with heparinized saline. All measurements were made more than a week after thoracotomy. Signals from the flow transducers were recorded by sine-wave flowmeters9 and displayed on a Grass polygraph (model 5) and sometimes also on a photographic recorder (Electronics for Medicine model DR 8). The electrocardiogram was usually sampled from one of the implanted flow transducers though sometimes standard limb leads were used.

We studied nine healthy active dogs weighing...
18 kg to 24 kg with normal pressures in the right and left atria, pulmonary artery, and aorta. They had normal hemoglobin concentrations, white cell counts, hematocrits, and blood volumes as determined by Cr$^{41}$-tagged red cells. Chest X ray after thoracotomy showed no evidence of lung collapse, pleural effusion, or any complication other than pleural thickening.

In five dogs the load against which the left ventricle contracted was altered by inflating and deflating a balloon attached to a catheter that had been inserted into the femoral artery under local anesthesia and advanced to the midthoracic aorta. Inflation and deflation of the balloon was done by hand using an attached syringe. After a control period (usually half a minute) of continuous recording during a steady state, the balloon was suddenly inflated with known volumes of carbon dioxide so as to occlude partially the aorta. The increased aortic impedance was maintained for 10 to 30 seconds, and then the gas was rapidly withdrawn from the balloon. It was possible to do this in four dogs when they were fully conscious; in the fifth, light thiopental sodium (Pentothal) anesthesia was required. These maneuvers did not appear to distress the unanesthetised dogs and in fact no outward reaction was detectable in them. Changes in aortic impedance were reflected in pressures recorded in the aorta just upstream from the balloon so that the time of the impedance changes could be determined accurately.

To obtain sudden reductions from a normal level of aortic impedance, in the other four dogs a bypass graft was sewed onto the abdominal aorta at a laparotomy a week after implantation of a single aortic transducer. During continuous recording, the graft was opened to the atmosphere for one or two beats. The blood ejected was replaced before repeating the experiment. In three animals this was done under general anesthesia, but we allowed the fourth to recover, and 36 hours later gently exposed the graft (which lay in a subcutaneous pouch) under local anesthesia. We have called this the mean systolic outflow resistance. We have called this the mean systolic outflow resistance. Since inflation and deflation of the balloon and clamping and unclamping of the aortic graft probably changed the capacitive and inertial components of the aortic system, we have throughout this paper spoken of aortic impedance and not aortic resistance.

As a measure of the load, the resistance against which the left ventricle ejected was determined for each beat. The mean aortic pressure during the period of ventricular ejection was obtained by planimetry and was divided by the stroke volume of the corresponding beat; this value was related to the ejection time and expressed in mm Hg/ml of flow per second of ventricular ejection. We have called this the mean systolic outflow resistance. Since inflation and deflation of the balloon and clamping and unclamping of the aortic graft probably changed the capacitive and inertial components of the aortic system, we have throughout this paper spoken of aortic impedance and not aortic resistance. We have called levels of impedance normal when they have not been artificially altered during the experiment. These normal levels vary from dog to dog.

**CALIBRATION**

The flow transducer records the instantaneous flow per second of ventricular ejection. We have called this the mean systolic outflow resistance. Since inflation and deflation of the balloon and clamping and unclamping of the aortic graft probably changed the capacitive and inertial components of the aortic system, we have throughout this paper spoken of aortic impedance and not aortic resistance. We have called levels of impedance normal when they have not been artificially altered during the experiment. These normal levels vary from dog to dog.

*Telco, Inc., Gentilly, France. Distributed in the U.S.A. by Dallons Laboratory, Inc., Los Angeles, California.
mean cross-sectional velocity of the blood moving through it,\textsuperscript{11} and since the vessel diameter is held constant by the transducer, velocity is directly proportional to the volumetric flow rate. The flow transducers were calibrated for each animal by recording dye dilution curves simultaneously with the flow signals. Three dye dilution curves were inscribed during the steady states at different levels of cardiac output in each animal. The relationship between the calculated flow per second and the mean flow signal was linear, and passed through the origin for each animal. We assumed that the total output during the inscription of the curves was the same for each ventricle. When allowance was made for the vessel wall thickness, using McDonald's formula,\textsuperscript{12} the cross-sectional area of the vessel, and thus the mean instantaneous velocity, could be calculated.

**ANALYSIS OF DATA**

All experiments were conducted when the animals were lying quietly. When impedance was changed during systole or diastole, a left ventricular beat before the change was compared with the one after. Pairs of beats were analyzed when the diastolic filling time for each was the same. Usually left ventricular stroke volume did not vary with respiration and consecutive beats could then be analyzed. When there was such a variation the beat after the change was compared with a beat in the same phase of the preceding respiratory cycle, provided that the variation of stroke volume with respiration had been constant for several respiratory cycles. Effects on each ventricle were also analyzed for the succeeding few beats up to the beginning of the baroreceptor response, and these beats were compared with those immediately before the change in impedance. The variables measured were stroke volume, peak flow, peak velocity, peak acceleration of ejected blood, backflow, the duration of ventricular ejection, and ventricular and aortic pressures.

In the five animals whose pressures were measured with high fidelity (with the Teleb catheter-tip manometer) and recorded photographically, external stroke work and power were calculated and the duration of the phases of systole was measured from the pressure record and the simultaneously recorded flow signal. The isovolumetric phase was measured from the onset of the pressure rise to the beginning of ejection, systole from the beginning of the pressure rise until the end of ejection, and ventricular relaxation from the end of ejection until the intraventricular pressure fell.

**FIGURE 1**

Change in aortic impedance. Stroke volume of left ventricle is reduced in beat after inflation of balloon and backflow wave is deeper and of shorter duration. There is no change in output of the right ventricle before rate change. Central volume is increased (see text). With the onset of bradycardia, stroke volume on both sides of the heart increases. Second beat after slowing of the heart is ectopic. ECG was recorded from one of the flow transducers.

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### TABLE 1

**Effect of Changes in Impedance During Diastole on Time Relationships of Mechanical Events During Systole**

<table>
<thead>
<tr>
<th>Beat</th>
<th>Systolic outflow resistance</th>
<th>Stroke volume</th>
<th>Ventricular contraction and relaxation</th>
<th>Isovolumetric contraction</th>
<th>Ejection time</th>
<th>Ventricular relaxation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm Hg/ml/sec</td>
<td>ml</td>
<td>msec</td>
<td>msec</td>
<td>msec</td>
<td>msec</td>
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<tr>
<td>1 Control</td>
<td>.60</td>
<td>24.0</td>
<td>243</td>
<td>45</td>
<td>131</td>
<td>67</td>
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<td>17.0</td>
<td>264</td>
<td>50</td>
<td>124</td>
<td>90</td>
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<tr>
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<td>18.7</td>
<td>256</td>
<td>71</td>
<td>120</td>
<td>65</td>
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<tr>
<td>2 Impedance reduced</td>
<td>.48</td>
<td>27.8</td>
<td>246</td>
<td>50</td>
<td>144</td>
<td>52</td>
</tr>
<tr>
<td>1 Control</td>
<td>.62</td>
<td>21.0</td>
<td>259</td>
<td>69</td>
<td>126</td>
<td>64</td>
</tr>
<tr>
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<td>25.5</td>
<td>255</td>
<td>64</td>
<td>136</td>
<td>55</td>
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</tbody>
</table>

* Three experiments in two dogs.

### Results

**EFFECT OF A SUDDEN INCREASE IN AORTIC IMPEDANCE**

Whenever impedance was increased in diastole the stroke volume of the left ventricle substantially decreased in the following beat, and pressure increased (fig. 1). The peak velocity and peak acceleration of ejected blood were also uniformly diminished, and the ejection time was always shorter. Impedance changes in early systole produced these effects in the same beat. As the phase of isovolumetric contraction was either unchanged or only slightly increased, the time from the onset of contraction to aortic valve closure was shortened. However, the relaxation of the ventricle, as measured from aortic valve closure to the end of the fall in intraventricular pressure, was prolonged, so that when compared with the control beat the total duration of contraction and relaxation of the ventricle was either unchanged or, more often, slightly prolonged (table 1).

The shape of the negative deflection in early diastole on the flow curve changed. The deflection became deeper and of shorter duration, but its area was not appreciably different from that of the control beat. However, the small positive deflection which immediately follows the negative deflection was smaller than in the control beat, so that there was generally a small increase in net backflow in early diastole.

The changes persisted for one, two, or three beats, and during this time there was no significant alteration in the performance of the right ventricle. There was, therefore, an increase in the amount of blood between the two flow transducers at this time, that is, an increase in pulmonary left heart blood volume (fig. 1). Then, with the onset of bradycardia (presumably due to baroreceptor response) stroke volume, peak velocity, acceleration, and ejection time on both sides of the heart increased.

Slowing of the heart was usually observed by the third beat after the change, and occasionally by the second (fig. 1). The average delay before onset of the rate change in 20 experiments was 0.8 second. At the heart rates occurring in these experiments (usually 120 to 140/min) rate changes were never seen in the first beat after the impedance change. When the heart rate slowed the stroke volume increased to considerably greater values than in the control beats (fig. 1). Peak velocity and peak acceleration were also greater and the ejection time longer. The bradycardia was always maximum at the time of onset; after about five seconds the heart rate tended to increase, though it always remained slower than in the control period. With this relative increase in heart rate the stroke volume then...
decreased though it usually remained higher than in the control period before inflation of the balloon. There was, however, a reduction in cardiac output, the average being 27%, while the balloon remained inflated.

In one animal 30 ml of blood was injected rapidly into the aorta through the abdominal aortic graft, under local anesthesia. Six experiments were performed. The results were qualitatively the same as those obtained by balloon inflation.

**EFFECT OF A SUDDEN REDUCTION IN AORTIC IMPEDANCE FROM AN ABOVE-NORMAL LEVEL**

An increase in heart rate, presumably due to the baroreceptor response, usually occurred after the second and sometimes after the first beat following the impedance change; the average delay in 20 experiments was 0.7 second.

There was a significant increase in the left ventricular stroke volume, peak velocity and acceleration of the ejected blood and the ejection time was longer in the first two or three beats after the change (fig. 2). When the reduction occurred in early systole these effects were seen in the same beat. The longer ejection time was associated with shorter periods of isovolumetric contraction and ventricular relaxation so that the total duration of contraction and relaxation of the ventricle in that beat was either unchanged or more often slightly abbreviated (fig. 3, table 1). The right ventricle was not affected during this time.

The backflow wave became less deep but of slightly longer duration so that its area was not appreciably different from that of the control beat (fig. 3). The small positive deflection which immediately follows the negative

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**FIGURE 2**

*Reduction in aortic impedance. Stroke volume, peak velocity (and therefore peak flow rate) increase in beat C, the beat after the change in impedance. Heart rate increases several beats later. Positive deflection immediately following backflow wave is larger than in the control and the ejection time longer. See also figure 3. Beat A may be compared with beat B or beat C. It is however more valid to compare it with beat C (see text) since beat B occurs in mid inspiration, which can be seen from the atrial trace, and end diastolic pressure appears lower. Beats A and C occur at identical phases of expiration and have equal end diastolic pressures. Unlabeled trace (channel 5) is an ECG taken from the flow transducer.*
FIGURE 3
Reduction in impedance between beats. In beat B the periods of isovolumetric contraction and relaxation are shortened and that of ventricular ejection is lengthened. Total duration of contraction and relaxation was 0.285 second in beat A and 0.265 second in beat B. Other changes resemble those in figure 2. Peak acceleration increases in beat B. Changes in shape of backflow wave can also be seen.

FIGURE 4
Effect of aortic flow of opening and closing an abdominal aortic graft (for description see text). Arrows show when the graft was opened and closed.
External work in successive beats (for description see text). Impedance increased between beats. External work is proportional to the area enclosed by each curve. Area is clearly less in the graph of the beat after change in impedance.

deflection was usually larger than in the control beat so that there was generally a small reduction in net backflow in early diastole.

EFFECT OF SUDDEN REDUCTION IN AORTIC IMPEDANCE FROM A NORMAL LEVEL

The graft was opened to the atmosphere for one or two beats and then clamped. It was usually opened in diastole, but in four experiments it was opened during systole. In every experiment stroke volume, peak velocity, and ejection time increased, either in the succeeding beat, or in the same beat when the change was in early systole. The later in systole the reduction was produced, the less was the effect on that beat and the greater the change in the succeeding one. The acceleration, measured in two animals, increased. When the graft was kept open for two beats, the second beat usually, but not invariably, showed the same change relative to the control beat (Fig. 4).

The changes in the phases of ventricular contraction and relaxation and in the form of the backflow wave in early diastole were similar to those seen when the impedance was reduced from an above-normal level.
Whenever the impedance was increased between beats the external work produced during the second beat was appreciably less than in the control. An example of this is shown in figure 5. Here, for an increase in systolic outflow resistance from 0.76 to 0.87 mm Hg/ml/sec, the external stroke work decreased from 4,000 to 3,390 g cm. When the impedance was then reduced from this elevated level the stroke work was substantially increased and exceeded the value found before the balloon was inflated. At this time the outflow resistance was always less than before the balloon was inflated, presumably due to vasodilatation. When the impedance was reduced from a normal level by opening the aortic graft, only small decreases (average 4%) in external work were produced. These results are summarized in figure 6, and the mean values after increases and decreases in impedance from normal levels in figure 7.

The external power of the ventricle changed in the same direction as did the external work in every experiment. The decrease in external power after reducing the impedance from normal was relatively greater than the reduction in external work (fig. 8).

Discussion

In general, the results of any maneuver were consistent in different dogs; furthermore, the consequences of opening the aortic graft were qualitatively similar with and without anesthesia. It is also significant that similar responses to increases in impedance were obtained by inflating a balloon in the thoracic aorta and by rapid infusion of blood into the abdominal aorta.

Since the first beat, after impedance was altered, occurred before any change in rate, we believe that the responses observed during these beats were not influenced by changes in the balance of nervous control. This assumption implies that changes in the discharge of sympathetic impulses to the ventricle and vagal and sympathetic impulses to the atrium do not take effect more rapidly than impulses which pass to the sino-atrial node and alter heart rate.

Until the onset of the bradycardia, presumably due to baroreceptor response, changes in aortic impedance had no effect on the right ventricle in our experiments. This can be seen in figure 1. Therefore, when impedance first increased, the volume of blood between the two transducers increased, and this increment was returned to the systemic circulation when the impedance was reduced. In this experiment (fig. 1) we measured the
pulmonary left heart volume by the dye dilution technique immediately before inflating the balloon, so that from the difference between the outputs of the ventricles the change in pulmonary left heart volume could be quantitated. It amounted in this instance to an increase of 5%. With respect to these mechanical changes the ventricles were working independently, or “out of phase.” This is additional evidence against involvement of autonomic activity in the immediate response to change of impedance, for then we would have expected right ventricular stroke volume to change. With the onset of the reflex response the ventricles changed together, or “in phase.”

The changes in shape of the initial backflow wave with increases in impedance are consistent with the expected response to an increase in aortic pressure. The small net increase in backflow cannot be accounted for by reflux into the ventricle, since the area enclosed by the initial backflow wave was not greater than in the control beat. The increased backflow was presumably due to greater coronary arterial perfusion.

The immediate effects of the impedance changes on stroke volume were similar to those found in isolated heart preparations for the short period (0.7 to 0.8 sec) that elapsed before alterations in heart rate. Similarly the inverse relationship between impedance and ejection time was confirmed in the intact and conscious dog. With a rise in impedance of the order produced in these experiments, there was minimal delay in the opening of the aortic valve, since it opened at the time of the most rapid rise in intraventricular pressure, but the aortic valve closed earlier so that the ejection time was shorter. We believe it is a reasonable assumption that the end diastolic volumes in the beat before and the beat after the change in load were the same. Therefore, changes in the duration of ejection, stroke volume, and consequently end systolic ventricular volume appear to be chiefly the mechanical consequences of the change in load. This is in accord with the findings of Holt who showed a linear relationship over a wide range between the force acting on the ventricular wall at the end of ejection and the calculated length of ventricular muscle fibers at that time.

After the immediate response it appeared that in each of these experiments alterations in heart rate and hence ventricular filling were much more important in regulating the force of ventricular contraction than any changes in atrial and ventricular contractility. For example, when the pressure in the carotid sinus was high following inflation of the balloon there was presumably a decrease in atrial and ventricular contractility, yet the result was bradycardia with a marked increase in stroke volume. Peak velocity and acceleration were greater and ejection time longer and since the aortic pressure was appreciably higher, stroke work was greatly increased.

**RELATIONSHIPS BETWEEN LOAD AND THE WORK AND POWER OF THE VENTRICLE**

In using systolic outflow resistance as an indication of the load we realize that this is an average value, since an equilibrium state is not reached in one beat; the same objection applies if mean ejection pressure is used. Peak systolic pressure on the other hand occurs at only one point in systole. When work and power were plotted against each of these, the same type of response was obtained. This was to be expected since each is related to the load and alters in the same direction as the load. We decided to use mean systolic outflow resistance as we have defined it since flow contributes to the load and this measurement relates flow and pressure at the aortic valve.

Our results indicate that under the conditions of ventricular filling and neurohumoral control which pertained during these experiments, the left ventricle functions near the peaks of the curves relating external work and power to load. Thus stroke work and stroke power are maximum when the ventricle contracts against a normal load.

In a recent study Imperial et al., using an isolated dog heart preparation, produced changes in outflow resistance between successive beats and measured aortic flow and pressure. They found that large increases in outflow resistance resulted in a fall in external work and power, whereas with moderate increases in resistance the results were variable.
They suggested that this might be explained if the control values represented points near the peak of a curve relating work to outflow resistance, and those obtained after large increases in resistance, points on the descending limb. It is significant that in their experiments a low outflow resistance was chosen as the control, the aortic pressure being of the order of 125/20 mm Hg. This emphasizes the difference between the isolated and the fully intact preparation since it is clear that in these hearts a normal outflow resistance would have produced values for stroke work and stroke power well down on the descending limbs of their work-load and power-load curves.

For a given load a contraction from a greater initial length of muscle fiber produces within limits more work and power. The work and power of the heart are also influenced by changes in neural and humoral stimulation. Assuming that all these findings are applicable to the intact conscious animal the work-load and power-load curves at any one time are a function of all these factors. It was, therefore, interesting that when the increased load was maintained in our experiments until a new steady state was reached, usually for 30 seconds, a sudden decrease then in load was always accompanied by a marked increase in external work and power. At this time the left ventricle was functioning on the descending limbs of the work-load and power-load curves. Despite probable changes in filling and sympathetic stimulation of the ventricle and definite vasodilation — on release of the balloon the systolic outflow resistance was always less than before inflating the balloon — the work-load and power-load relationships were not adjusted to permit the ventricle to function at the peak of these curves. This could have been because the increase in load produced was beyond the physiological range, but this is unlikely because the results were similar over a wide variety of load increases. It could have been because the time allowed for readjustments was insufficient, though this would involve mechanisms which take more than 20 to 30 seconds to reach a new equilibrium. In either case our results give some idea of the limitations of the adjusting mechanisms — if indeed the various control mechanisms are integrated to produce adjustments of this type. Our study seems to suggest that fairly rapid adaptations to a change in systemic load can only be brought about with the ventricle functioning on less ideal parts of its work-load and power-load curves.

Summary

We have investigated the effects of sudden changes in the load against which the left ventricle contracts in healthy conscious dogs. During a steady state, initial responses were assessed by comparing the beat before with the beat after such a change. Flow was measured by electromagnetic flowmeters and pressure usually by a catheter-tip transducer.

Results show that under the conditions of these experiments the curves relating external work and power to load are consistent with the parabolic relationship shown for isolated hearts and muscle strips and that in each case the left ventricle normally functions near the peak of the curve.

When an increased load was maintained until a new steady state was reached the left ventricle still functioned on the descending limbs of what presumably were different work-load and power-load curves. It was concluded from this that either the increase in load was too great or the time too short for reflex humoral and intrinsic mechanisms to readjust and permit the ventricle to function again at the peak of each curve, or that the circulatory system does not make relatively rapid adaptations in this way to an increase in systemic load.

The immediate effects of changes in load on left ventricular stroke volume were similar to those seen in isolated preparations. Stroke volume varied inversely with the load. Stroke volume changes were accompanied by changes in the duration, rate, and velocity of ejection. The duration of the isovolumetric phase was affected little but the period from valve closure to the end of ventricular relaxation varied with the load so that the total duration of contraction and relaxation of the ventricle was rela-
AORTIC IMPEDANCE AND VENTRICULAR PERFORMANCE

...tively unchanged, though an increase in load did tend to prolong it.

Before the onset of the baroreceptor response the right ventricle was not affected, the two ventricles acting independently in relation to all these changes.

Acknowledgment

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