Distribution of coronary arterial capacitance in a canine model

ALAN S. LADER, REBECCA S. SMITH, GEORGE C. PHILLIPS, JAMES E. McNAMEE, AND FRANCIS L. ABEL

Department of Physiology, University of South Carolina
School of Medicine, Columbia, South Carolina 29208

Lader, Alan S., Rebecca S. Smith, George C. Phillips, James E. McNamee, and Francis L. Abel. Distribution of coronary arterial capacitance in a canine model. J. Appl. Physiol. 84(3): 954–962, 1998.—The capacitative properties of the major left coronary arteries, left main (LM), left anterior descending (LAD), and left circumflex (LCX), were studied in 19 open-chest isolated dog hearts. Capacitance was determined by using ramp perfusion and a left ventricular-to-coronary shunt diastolic decay method; both methods gave similar results, indicating a minimal systolic capacitative component. Increased pericardial pressure (PCP), 25 mmHg, was used to experimentally alter transmural wall pressure. The response to increased PCP was different in the LAD vs. LCX; increasing PCP decreased capacitance in the LCX but increased capacitance in the LAD. This may have been due to the different intramural vs. epicardial volume distribution of these vessels and a decrease in intramural tension during increased PCP. Increased PCP decreased LCX capacitance by ~13%, but no changes in conductance or zero flow pressure intercept occurred in any of the three vessels, i.e., evidence against the waterfall theory of vascular collapse at these levels of PCP. Coronary arterial capacitance was also linearly related to perfusion pressure.

coronary blood flow; coronary vascular properties; pericardial pressure; coronary vascular compliance

THE ELASTIC NATURE of the coronary vasculature results in a capacitative factor in the mechanics of coronary flow. The magnitude and importance of the arterial component of this capacitance have been variously estimated to range from ~0.01 to 0.02 ml·mmHg⁻¹·100 g⁻¹ (6, 7). The location of the arterial portion of the capacitance has, however, been a source of controversy. Some workers believe it to be largely endocardial (17, 28), whereas others report it as a major epicardial element (29). Similarly, theoretical models to explain the relationship among coronary flow, driving pressure, and intramyocardial pressure have implicated coronary arterial capacitance to a degree varying from little significance for the waterfall model (13) to great significance for the time-varying elastance (20) and intramyocardial pump models (27).

Our laboratory has recently reported on the effects of pericardial pressure (PCP) on left circumflex (LCX) coronary flow (1). An increase in PCP was used to alter epicardial capacitance; when the coronary arteries were pump perfused, an increase in PCP, with left ventricular pressure (LVP) constant, resulted in an increase in characteristic impedance. Along with this change in characteristic impedance, there was an 8–12% decrease in epicardial capacitance. However, increasing PCP alone did not alter the coronary vascular resistance (1); according to the vascular waterfall theory, increasing the pressure on the surface vessels should have collapsed them and increased coronary resistance.

This study was undertaken to determine the arterial distribution of coronary vascular capacitance and resistance in the dog heart. Specifically, we measured capacitance and resistance in each of the three major coronary arteries: the left main (LM), LCX, and left anterior descending (LAD) arteries. Our rationale was based on data that although the LCX and LAD have similar epicardial volumes (11, 24), total LCX volume is greater (26, 24), and therefore more of the LCX volume is located intramurally. We measured the pressure-flow relationship in each of these arteries to determine whether their anatomic differences would significantly influence their coronary vascular properties.

METHODS

Nineteen mongrel dogs of either sex [20–30 kg, 26.1 ± 1.0 (SE) kg] were anesthetized with pentobarbital sodium (30 mg/kg). A tracheotomy was performed, and the trachea was cannulated. The animals were artificially ventilated with 15 ml/kg of room air, supplemented with O₂ (3–5 l/min), at a rate of 16 breaths/min, and the chest was opened through a midline thoracotomy. The heart and lungs were isolated by cannulating the brachiocephalic artery and attaching the cannula to a reservoir for controlling afterload (Fig. 1). A branch from the reservoir tubing allowed blood to flow through a heat exchanger, peristaltic pump, and debubbler and back to the right ventricle. The peristaltic pump was used to control venous return to the right heart. After the heart was attached to the perfusion apparatus, the left subclavian artery was ligated near its origin and the thoracic aorta was ligated immediately after the origin of the left subclavian. The superior vena cava, inferior vena cava, and azygous vein were then ligated. Arterial pressure was controlled by adjusting the height of the reservoir, whereas venous return was controlled with the bypass pump; the bypass pump, therefore, set the level of cardiac output. The atrioventricular node was sectioned by electrocautery, and the heart was paced at 120 beats/min. The lungs were then ventilated with 95% O₂-5% CO₂, the latter gas being required in the isolated organ. A constant infusion of calcium gluconate (0.06 mg/ml), norepinephrine (1 µg/ml), and glucose (30 mg/ml) was given at a rate of 1 ml/min to prevent depletion of these metabolites and maintain stability of the preparation. Blood gases were measured periodically and O₂, pH, and CO₂ were maintained within physiological ranges. This stable heart-lung preparation has previously been described in detail (2).

Aortic and central venous pressures were measured by strain gauges (Statham Instruments, Oxnard, CA) through fluid-filled catheters inserted into the aortic outflow line (Fig. 1) and into the right atrium. In some experiments, an
electromagnetic flow probe (Carolina Medical, King, NC) was placed around the pulmonary artery for measurement of cardiac output. A miniature high-frequency strain-gauge catheter (Millar Instruments, Houston, TX) was introduced into the left ventricle.

After the heart was isolated, the LM (n = 6), the LCX (n = 7), or the LAD (n = 6) was selected on a random basis, cannulated, and perfused with blood via a separate perfusion pump. The perfusing blood was drawn from the bypass system after it passed through the heat exchanger but before it reached the venous return pump (Fig. 1). The perfusion pump had the ability to be servo controlled, allowing for control of coronary perfusion pressure. Between experimental perturbations, coronary perfusion pressure was maintained constant at 100 mmHg. Coronary perfusion pressure was measured by a strain gauge via a fluid-filled catheter inserted into the perfusion line; coronary flow was measured by using an ultrasonic flowmeter (Transonic Systems, Ithaca, NY) with the flow-through probe also inserted into the coronary perfusion line. The data were digitized at 250 samples per second for each channel and recorded by using a personal computer and CODAS data-acquisition and -analysis software (DATAQ Instruments, Akron, OH). Data are reported as means ± SE.

Coronary capacitance was analyzed by using a variation of the method described by Canty and co-workers (6, 7). Their method assumes that capacitance can be lumped into a single parameter. A function generator was used to control the servo-controlled coronary perfusion pump. A half-wave-rectified triangular wave drove the pump to produce perfusion pressures that increased and decreased at a virtually constant rate (dP/dt) (Fig. 2). The flow is slightly out of phase with the pressure; the phase difference is related to the capacitance of the coronary vessel. When flow is plotted as a function of pressure divided by the period of constant dp/dt (exclusive of the part of the waveform where the pressure is changing direction) (Fig. 3), the observed difference in the pressure-flow relationship at any given pressure is related to capacitance (6, 7). Capacitance (C) can then be determined by using the following equation (6, 7)

$$C = \frac{\dot{Q}_u - \dot{Q}_d}{dP_u/dt - dP_d/dt}$$

where $\dot{Q}_u$ is the flow while the pressure is increasing and $\dot{Q}_d$ is the flow while pressure is decreasing. The first derivatives of the perfusion pressure are dP/dt and dP/dt, corresponding to increasing and decreasing pressure, respectively. According to Canty and co-workers (6, 7), the coronary capacitance will be independent of dP/dt up to ~50 mmHg/s; therefore, the ramp pressures were generated at 15–20 mmHg/s, well below this limit. The denominator of the above equation differs from Canty's equation (6, 7) in that we have separated dP/dt and dP/dt. Canty's system was able to produce a dP/dt that was equal to $-dP/dt$, making their denominator $2 \times dP/dt$. We separated the individual dP/dt components to minimize errors in the calculations.

These relationships were analyzed in coronary vessels maximally dilated with adenosine (5 mg/min into the coronary perfusion line). The reactive hyperemic response to an occlusion of the coronary vessel was used to determine maximum vasodilation; if reactive hyperemia were absent, the vessel was maximally vasodilated: low doses were sufficient in the isolated heart preparation.

Flow-pressure relationships were analyzed by using the mean of the pressure and flow waveforms (Fig. 3). With the capacitance and dP/dt known, one can obtain a capacitance-free flow-pressure relationship. Capacitance has been shown to be a function of perfusion pressure (6, 7); therefore, we used a linear regression analysis to evaluate the significance of the capacitance change over a wide range of perfusion pressures (5). Conductance of the coronary vascular bed was obtained from the slope of the capacitance-free pressure-flow relationship. The pressure at zero flow (PF = 0) was not extrapolated but was measured before the ramp infusion pump was started.

Epicardial capacitance was altered by the method previously described by our laboratory (1) of application of positive
PCP. The dog’s chest was closed and sealed airtight. A metal tube with a 3/8-in. internal diameter was placed through the chest wall to act as a pressure inlet. This pressure inlet was attached to a pressurized air source. A strain gauge was used to monitor PCP; pressure-flow plots were obtained at low (0 mmHg) and at high PCP values (25 mmHg). The inlet was open to atmosphere for low PCP; for high PCP, the intrathoracic pressure was raised to 25 ± 1 mmHg (the range was 20–30 mmHg).

During diastole, the pressure in the ventricles increased as a result of the increase in PCP. PCP was, therefore, subtracted from the measured diastolic pressures. The measured LV end-diastolic pressure (EDP) minus PCP was more indicative of ventricular preload than was EDP alone. Similarly, coronary perfusion pressure was equal to the pressure generated by the infusion pump minus PCP. PCP was not subtracted from systolic ventricular pressure; during systole, ventricular pressure was coupled to the external reservoir, thus being essentially independent of PCP. Right atrial pressure was also measured and found to closely follow PCP; right atrial pressure was −0 mmHg at low PCP and 25 mmHg at high PCP.

The flow-pressure relationships obtained from the ascending and descending ramp experiments were normalized to the mass of the perfusion territory; the capacitance and conductance were normalized to 100 g of tissue. Total weight of the perfused tissue was obtained from the weight of the whole heart by using percentages for the LCX, LAD, and LM in dogs of 38.6, 32.3, and 83.5% of the whole heart weight, respectively, as described by Scheel and co-workers (26).

We also measured diastolic capacitance by using a method previously described by our laboratory (1). This was adapted from a technique used by Downey and Kirk (12) to measure blood flow in the myocardium during systole. They perfused the coronary vessels from a shunt in the left ventricle; endocardial perfusion, with this method, was reported to be minimal. Therefore, the capacitance of the endocardial vessels would have a very small effect on the measured flow, and it should allow us to primarily measure epicardial and myocardial capacitance.

To implement this procedure, a large catheter (22-Fr Bardic catheter; Bard, Murray Hill, NJ) was placed through the left atrial appendage and the mitral valve into the left ventricle. This catheter was attached to the coronary perfusion cannula, proximal to the flow probe and the pressure sensor (Fig. 1). When the shunt was open and the coronary pump line was clamped, the cannulated vessel was perfused directly from the left ventricle. The resultant coronary pressures and flows were high during systole and low during diastole, opposite of the normal physiological state (Fig. 4). The capacitance measurements made using
these left ventricular shunts were also done on maximally vasodilated coronary arteries by using adenosine.

Assuming a resistance-capacitance (RC) model, flow into the epicardial vessels is equal to

\[ \text{Flow} = \frac{P(t)}{R} + C \frac{dP(t)}{dt} \]

where \( P(t) \) is pressure as a function of time (t).

Because the shunt perfusion mimics an impulse function, the solution to the above differential equation is

\[ \text{Flow} = \delta(t) - Ae^{-t/\tau} \]

where the \( \delta(t) \) is the initial flow without capacitance, \( A \) is a constant, and the time constant (\( \tau \)) is equal to RC. During diastole, the opposite conditions occur; the driving pressure is directed out of the vascular bed (retrograde flow), into a low, fairly constant, pressure in the ventricle. This force decays as the capacitor discharges, and the decay in flow is assumed to be the discharge of the coronary capacitance through the constant resistance of the coronary cannula. (The cannula's hydraulic resistance was found after the end of each experiment by measuring the pressure drop in the cannula at a minimum of three different flow rates. A linear plot was obtained, and its slope was used as the resistance.) Dividing the time constant (RC) of the exponential decay of the coronary flow during diastole by the hydraulic resistance of the cannula yielded the diastolic capacitance. The diastolic flow data was obtained by starting from 20 ms after the diastolic peak and ending 12 ms before the start of systole. A nonlinear regression was used to calculate the time constant of the flow decay (4, 23); a zero flow asymptote was not assumed. The nonlinear regression procedure used the simplex algorithm from a published computer program (23).

Because the possibility of two (or more) distinct sites for capacitances exists (e.g., one representing epicardial capacitance and one representing intramyocardial capacitance), rather than a single lumped value, the nonlinear regression of a two-exponential function, which would result from a two-capacitance system (14, 15), was calculated for the diastolic flow decay and compared via an F-statistic to the single-exponential function. Adding the second exponential did not significantly improve the fit of the model (the P value for the F-statistic was not <0.05). Therefore, only a single

Fig. 3. Flow-perfusion pressure relationship from a representative ramp experiment at low pericardial pressure (PCP). Difference between pressure-flow relationship while pressure was increasing (dP/dt) vs. while pressure was decreasing (dP/dt) was used to calculate capacitance (C), conductance (slope of capacitance-free relationship), and pressure at zero flow (Pf=0). See text for method.

Fig. 4. Representative coronary flow and pressure, along with LVP, when coronary artery was perfused through LV shunt. Time constant of exponential decay was found for each beat, then divided by resistance of shunt to obtain capacitance. Diastolic portion of flow waveform (inset; Q) was fit to equation \( Q = A + B e^{-t/\tau} \) by using nonlinear regression, where \( \tau \) is the time constant used to obtain capacitance and A and B are regression coefficients.
capacitance could be observed by using flow data from the left ventricular shunt. Because the data were paired between low and high PCP, the change in capacitance was analyzed, as well as the absolute capacitance.

An analysis of variance (ANOVA) was used to evaluate the conductance and \( P_{F0} \) changes as well as capacitance from the left ventricular shunts (5). A paired Student’s t-test was used to evaluate the significance of other data (22). A \( P < 0.05 \) was considered significant. Where multiple comparisons were performed, a Bonferroni correction was used to protect the significance level (5, 22). The data are presented as means ± SE.

All experiments were performed in adherence to the “Guide for the Care and Use of Laboratory Animals” [DHEW Publ. No. (NIH) 86–21, Revised 1985, Office of Science and Health Reports, DRR/NIH, Bethesda, MD 20892].

RESULTS

Ramp experiments. Figure 5 shows a typical hemodynamic response to an increase in PCP; note the rise in EDP. Table 1 illustrates the change in cardiac function due to the increase in PCP. Cardiac function analysis was only performed in five of the seven animals with LCX cannulas and in four of the six animals with the LM cannula. As shown in Table 1, calculated EDP decreased significantly with increased PCP. We interpreted this as an indication of decreased preload; the decrease in preload was accompanied by a decrease in both cardiac output and cardiac work, indicating a downward shift of the Starling function curve.

Table 2 shows the conductance at low and high PCP for each of the coronary arteries under investigation. An increase in PCP did not induce a statistically significant change in the conductance of any of the coronary vascular beds in any of the three vessels. Table 2 also gives the \( P_{F0} \) intercept value at low and high PCP for each of the coronary arteries. Again, none of the three vessels showed a significant change when PCP was increased, suggesting, along with the conductance data, that the coronary vessels did not collapse at these levels of increased PCP.

When analyzed by the ramp method, total capacitance for all three vessels was related to perfusion pressure (Fig. 6). At ~80–100 mmHg, increasing PCP by 25 mmHg did not further alter capacitance. The maximally dilated vasculature may be fully distended at this perfusion pressure. At lower perfusion pressures, an increase in PCP caused a decrease in total capacitance of the LCX. However, an increase in capacitance was observed in the LAD when PCP was increased; the LM also showed a small but significant increase.

Because the low PCP data were paired with the high PCP data, a linear regression analysis was performed on the change in capacitance (Fig. 7). Since the variance was not constant as the perfusion pressures changed, a weighted least squares analysis was used with the variance as the weighting factor. The regression was significant for all three groups (\( P = 0.0002 \), \( P = 0.0001 \), and \( P = 0.045 \) for the LCX, LM, and LAD, respectively). The signs of slope and intercept for the LCX were opposite to those of the LAD and LM, i.e., the LCX response to increased PCP was opposite to that of the LM and LAD. The LM response was intermediate between that of the LCX and LAD.

An ANOVA was performed on the change in capacitance to investigate whether there were differences among the three arteries. The ANOVA was significant (\( P = 0.045 \)). A post hoc multiple comparison was used to investigate which vessels had different changes in capacitance. There were specific differences between the LCX and the LAD (\( P = 0.0001 \)). In addition, the capacitance change due to PCP for the LCX was different from that in the LM (\( P = 0.0075 \)), but the LAD results were not significantly different from those for the LM (\( P = 0.104 \)).
Shunt experiments. Capacitance of the coronary arteries was next analyzed by using the left ventricular shunt (Table 2). This method did not show any significant differences between the three arteries studied by a two-way ANOVA. (LAD was lower than LM at low PCP by t-test.) Therefore, the data from all three arteries were pooled, and a paired t-test was performed on the pooled data to investigate the change due to the PCP increase. At zero PCP and high PCP (25 ± 1 mmHg), the capacitance was 29.8 ± 7.2 and 25.0 ± 6.7 ml·mmHg⁻¹·100 g⁻¹·10⁻³, respectively. This change was significant (P < 0.05). The capacitance changed 11.8 ± 1.8% with an increase in PCP of ~25 mmHg. Two of the animals had very high capacitances by this method and were more than two SDs from the mean of the data. Without inclusion of data from these animals, the capacitance at zero PCP and high PCP was 21.1 ± 4.5 and 15.6 ± 2.2 ml·mmHg⁻¹·100 g⁻¹·10⁻³, respectively. This represents a 13.4 ± 1.9% change in capacitance. These values are similar to previous ones reported for the LCX alone (1).

The shunt experiments only measured capacitance during diastole at low perfusion pressures. Comparison of the capacitance measured by the left ventricular shunts vs. the LAD and LCX capacitance measured by the ramps gave similar results. Pooled capacitance measured by the shunt technique (when perfusion pressure was equal to diastolic pressure) at low PCP was 29.8 ± 7.2 ml·mmHg⁻¹·100 g⁻¹·10⁻³. Ramp-measured capacitance at 10-mmHg perfusion pressure (which is similar to diastolic pressure or coronary perfusion pressure with the shunt open) and zero PCP was 25.0 ± 9.9 and 30.9 ± 18.5 ml·mmHg⁻¹·100 g⁻¹·10⁻³ in the LCX and the LAD, respectively; i.e., the measured capacitances were not significantly different by the two methods.

Table 1. Cardiac function changes associated with an increase in pericardial pressure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left Circumflex (n = 7)</th>
<th>Left Anterior Descending (n = 6)</th>
<th>Left Main (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low PCP</td>
<td>High PCP</td>
<td>Low PCP</td>
</tr>
<tr>
<td>LVP, mmHg</td>
<td>98.6 ± 1.7</td>
<td>101.7 ± 6.6</td>
<td>93.6 ± 2.9</td>
</tr>
<tr>
<td>EDP, mmHg</td>
<td>5.9 ± 1.5</td>
<td>1.4 ± 1.3*</td>
<td>9.6 ± 1.0</td>
</tr>
<tr>
<td>MAP, mmHg</td>
<td>74.6 ± 3.2</td>
<td>74.6 ± 2.8</td>
<td>70.0 ± 2.0</td>
</tr>
<tr>
<td>CO, ml/min</td>
<td>66.8 ± 69</td>
<td>551 ± 53*</td>
<td>799 ± 66</td>
</tr>
<tr>
<td>CW, l·mmHg⁻¹·min⁻¹</td>
<td>69.9 ± 6.9</td>
<td>63.4 ± 8.2*</td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SE. n, No. of dogs; PCP, pericardial pressure; LVP, left ventricular pressure; EDP, left ventricular end-diastolic pressure (measured minus PCP); MAP, mean arterial pressure; CO, cardiac output; CW, cardiac work. High PCP (25 mmHg) was compared with low PCP (0 mmHg) for each experiment group by using Student's t-test. CO and CW were obtained in 5 of 7 dogs in left circumflex group, in 4 of 6 dogs in left main group, and in none in left anterior descending group. *P < 0.05 vs. low PCP. † No comparison made.

DISCUSSION

A major finding in this study was the opposite response of the LCX bed vs. the LAD when the PCP was increased. Capacitance of the LCX bed decreased, whereas that of the LAD bed increased (Figs. 6 and 7). The combined LM vasculature showed an intermediate response, i.e., little change in capacitance. The reason for this discrepancy in response, and its potential importance to understanding coronary function, is not entirely clear. The septal artery may play a role, but probably only a minor one. According to Scheel et al. (26), it perfused 12.6% of the weight of the heart (15.2% of the mass perfused by the LM). In some cases our cannula may have blocked, or partially blocked, flow into this channel. The septal artery and the LAD perfuses part of the right ventricular free wall and right ventricular portion of the septum (26) and is thus subjected to lower myocardial wall tensions. Chilian and Marcus (8) demonstrated that, during systole, flow in the septal artery may be retrograde while flow in the LM remains antegrade. Therefore, if backflow from this vessel is entering the LAD, it could lower the capacitance measured in that vessel and in the LM. However, the lower transmural wall pressure might act in the opposite direction to raise the capacitance.

We believe that a major reason for the difference in response of the LCX and LAD beds is the difference in anatomic distribution of the volumes in those beds. Several workers have shown, by using both casts (24, 25) and in vivo experiments (24), that the perfusion territory of the LCX is considerably greater than that of the LAD, accompanied by higher coronary flows. Scheel et al. (26), for example, report 38.6% of heart weight in dogs is perfused by the LCX vs. 32.3% for the LAD; other workers show similar results (24). On the other
hand, casts of the epicardial vessels alone, with vessels smaller than 200 µm occluded, show similar volumes for the two beds: 0.63 ± 0.04 for the LAD and 0.75 ± 0.08 for the LCX (ml/100 g heart) (11). Therefore, the LCX has a greater intramyocardial volume in its distribution than does the LAD. During systole, the transmural pressure is reduced by the application of PCP, i.e., LVP is functionally lower (see below) and epicardial pressure is increased by 25 mmHg (Fig. 5). The resultant decrease in transmural pressure should allow for greater capacitance in the intramyocardial vessels. This effect was, however, most prominent in the vessel having a lower intramyocardial volume, perhaps because this smaller volume was more sensitive to transmural tension. Although this explanation is not entirely satisfying, it is, at present, the only one that seems to explain these findings.

The decrease in EDP (corrected for PCP), cardiac output, and cardiac work with an increase in PCP, suggests that the hearts were shifted to a lower operating point on a Starling function curve. Therefore, fiber length and intramyocardial stress may have been less accompanied by a lower ventricular volume and transmural pressure. The lower ventricular wall tension would allow volume to be displaced into the intramural coronary vessels, resulting in an increase in capacitance. Intramyocardial pressure decreases in a semilinear manner with ventricular pressure and distance from the endocardium (27). If PCP were elevated, the transmural pressure gradient would decrease. If ventricular volume also decreases, associated with lower filling pressure, the net result would be a decrease in transmural tension. In diastole, during high PCP, transmural tension would decrease somewhat (Table 1), and the radius of the heart would decrease. During systole, transmural tension would decrease by approximately the value of PCP. Even if the end-systolic dimensions are similar, the net result would be a decrease in tension.

In systole, the force of contraction also contributes to intramyocardial tension (31). During high PCP, the contracting myocardium has to develop 25 mmHg less driving pressure to overcome the same afterload, the rest of the energy being supplied by the external pressure. Therefore, contractility can decrease, from a...
lower EDP, and intramyocardial tension due to contraction can also decrease. Thus, in these experiments, epicardial vessel capacitance was decreased by the increase in PCP due to the compressive force of the PCP directly on the vessels. However, intramyocardial vessel capacitance, determined to a greater extent by intramyocardial tension, should increase. The measured capacitance was resultant of both epicardial and intramyocardial capacitance.

Because the intramural volume of the LAD is reportedly (11, 26) smaller than that of the LCX, the lower wall tension could dominate the capacitance measurement in that vessel. The effects of intramyocardial stress changes would be smaller in the LCX, where the compressive forces are distributed over a larger vascular volume. Moreover, because the LAD and LCX are in parallel, one would expect the measured capacitance of the LM to be the sum of these two vascular beds. (The LM itself was effectively occupied by the cannula). The capacitance of the LM was actually about one-half that of the LAD and LCX, suggesting that the LM capacitance is not simply the sum of the capacitances of the LCX and LAD. However, the capacitances were normalized to the weight of the perfusion territory; therefore, the two vascular beds in parallel must also be normalized; normalization would make the expected LM capacitance equal to the average of the LCX and LAD capacitances.

Relative to the possible importance of this discrepancy in transmural volumes, it may be involved in the coronary steel phenomenon seen in coronary arterial stenosis. Gallagher et al. (16) report that this results in redistribution of the vascular volume, i.e., blood flow from the subendocardium to the subepicardial regions. If the intramyocardial volume of the LCX were greater, it could perhaps handle the shift in flow more evenly across the myocardial wall, whereas the LAD volume would be rapidly compromised and shifted into epicardial vessels. If this analysis is correct, LAD stenosis should result in more severe subendocardial ischemia than LCX stenosis. The possibly beneficial effects of the increase in PCP seen in these experiments cannot readily be applied; a reduction in afterload would only further compromise the stenotic flow.

A decrease in left ventricular end diastolic volume with PCP is also consistent with earlier findings by Craig et al. (9) and by Crystal and co-workers (10); the latter group also reported a decrease in left ventricular contractile function. Although we did not measure the dimensions of the left ventricle, an increase in PCP produced by increasing intrathoracic pressure may also have decreased left ventricular filling due to compression of the pulmonary venous system. One difficulty with the ramp experiments is that the heart was beating throughout the duration of the ramps. Previous reports have demonstrated that impedance of the coronary vessels is constant through diastole (18) and does not change throughout the cardiac cycle (30). Therefore, our data should not be significantly different from ramp experiments done during long diastoles. At perfusion pressures of 30, 50, and 70 mmHg, Canty and co-workers (7) report that the total capacitance of the LCX (n = 10) was 20.0 ± 1.0, 14.7 ± 1.0, and 8.9 ± 0.8 ml · mmHg⁻¹ · 100 g⁻¹ · 10⁻³, respectively. Their perfusion pressure dP/dt was 30 mmHg/s, which is faster than the dP/dt in these experiments; Canty et al. have shown that this difference is not significant, but it is important not to use too fast a ramp. Our values for the LCX at these perfusion pressures and low PCP (n = 7) are 19.9 ± 7.5, 14.9 ± 5.2, and 9.8 ± 3.2 ml · mmHg⁻¹ · 100 g⁻¹ · 10⁻³, respectively, values very similar to those of Canty and co-workers. (The SEs are high because capacitance was unusually high in 1 of the 7 dogs. Without the data from the single dog, the values are 15.6 ± 1.8, 11.8 ± 0.9, and 8.0 ± 2.1 ml · mmHg⁻¹ · 100 g⁻¹ · 10⁻³, respectively.) The similar diastolic capacitances from the shunt experiments vs. the ramp experiments also indicate that capacitance must not be greatly altered during systole.

The left ventricular shunt experiments allow for a slightly different analysis of the effect of increased PCP on coronary flow. These results showed no difference between the capacitance of the LAD compared with that of the LCX. However, in the shunt, inflow to the coronary arteries was during systole, when most of the inflow is to the epicardial and subepicardial vessels (12). Because the volumes of this portion of the vascular beds are similar in the LCX and LAD (11), PCP should have had a similar effect on these beds. Using the shunt technique, we observed a decrease in capacitance in both beds of ~12–13%. This agrees with the previous finding in the intact animal by our laboratory (1).

The ramp experiments permitted calculation of the "waterfall pressure." Although flow was allowed to remain at zero for several seconds between ramps, we did not observe substantial changes in the perfusion pressure during this period (Fig. 2). Therefore, the P<sub>F=0</sub> appeared not to be significantly influenced by either the cardiac cycle or by PCP (Table 2). These results contradict the work of Satoh and co-workers (25) as well as that of Kingma and co-workers (19). Satoh and co-workers (25) reported a P<sub>F=0</sub> increase of ~15 and 30 mmHg with a PCP of 15 and 30 mmHg, respectively. Kingma and co-workers (19) reported an 10-mmHg increase in the P<sub>F=0</sub> with a 10-mmHg increase in PCP. However, we believe that the effective perfusion pressure is the difference between the external pressure (PCP) and the intravascular pressure. By using this method, P<sub>F=0</sub> did not change substantially with an increase in PCP (Table 2). The pressure in the right atrium was similarly increased by PCP; at a PCP of 0 mmHg, right atrial pressure was near zero and, at a PCP of 25 mmHg, it was 25 mmHg.

Coronary vascular resistance measurements were made by using effective perfusion pressure minus right atrial pressure; increasing PCP did not alter calculated resistance in any of the three vascular beds. This also agrees with the previous findings by our laboratory for the LCX (1) and indicates that the epicardial coronary vascular beds may be protected from collapse even at these low levels of PCP.
In summary, we have presented new evidence of the importance of intramyocardial pressure in influencing coronary capacitance. This effect was different in the LCX vascular bed vs. that of the LAD and indicates that capacitance in deeper vessels can actually increase without a reduction in LVP.

Conclusions. First, during ramp perfusion pressure experiments, the response of the LAD to an increase in PCP was different from that of the LCX. Increased PCP was assumed to decrease epicardial capacitance; in the LCX, this resulted in a decreased capacitance. In the LAD, however, an increase in PCP increased capacitance, perhaps due to an accompanying decrease in ventricular transmural forces.

Second, there was no change in either conductance or \( P_F \) when PCP was increased, which the vascular waterfall model of coronary circulation would predict. Therefore, the majority of the coronary arteries must be protected from collapsing either because of the low levels of PCP employed or their location downstream from the epicardial vessels.

Third, our results support the concept that intramyocardial stress influences coronary capacitance. Thus a model of the coronary circulation should include at least two arterial capacitances, one for the epicardial vessels and one for the intramural vessels.

Fourth, we have confirmed previous findings demonstrating that coronary arterial capacitance is inversely related to perfusion pressure.

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Present address of A. S. Lader: Renal Unit, Massachusetts General Hospital, Charlestown, MA 02129.

Address for reprint requests: F. L. Abel, Dept. of Physiology, Univ. of South Carolina School of Medicine, Columbia, SC 29208.

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