SUMMARY Previous studies have shown that left atrial pressure increases when measured relative to pleural pressure during positive end-expiratory pressure (PEEP). We studied the factors leading to this increase in anesthetized mechanically ventilated dogs. Cardiac output was maintained nearly constant before and during PEEP, and heart rate did not change. Left atrial pressure measured relative to pleural pressure rose by 2.5 ± 0.5 mm Hg (mean ± se) during PEEP. Pericardial pressure did not rise more during PEEP than did pleural pressure, indications that there was a true increase in transmural left atrial pressure. With PEEP there was no change in left ventricular diastolic volume as measured by cineangiography and cinefluorography of lead markers implanted in the subendocardium. Left ventricular contractile function, as measured by ejection fraction, also was unchanged. Analysis of the ventricular axes showed an increase in the ratio of septal-lateral to apex-base and anterior-posterior axes with PEEP, indicating a shape change in the left ventricle. Plots of left ventricular volume against left atrial transmural pressure confirmed that there was a shift in the left ventricular pressure-volume curve during PEEP. Thus, the rise in left atrial transmural pressure during PEEP appears to have been caused by a change in left ventricular diastolic pressure-volume properties. We suggest that these changes in the left ventricle may be related to the effects of PEEP on the right ventricle which, in turn, influence the left ventricle.

POSITIVE end-expiratory pressure (PEEP) is known to decrease cardiac output (CO). Usually, this is attributed to transmission to the right atrium and great veins of the higher pleural pressure during PEEP which impedes venous return (Ashbaugh and Petty, 1973; Cournand et al., 1948; Lutch and Murry, 1972). However, other mechanisms appear to be operative as well. When right and left atrial pressures were measured relative to pleural pressure, thus measuring "effective" or "transmural" pressure, either no change or an increase was found during PEEP (Scharf et al., 1977; Scharf and Ingram, 1977) even with sizable decreases in venous return. Furthermore, these increases in transmural pressures depended on the degree to which lung volume increased at end expiration. These observations suggested to us as well as to others (Manny et al., 1978; Prewitt and Wood, 1977; Robotham et al., 1977) that a change in function of the right and left ventricles occurs when PEEP is associated with increased functional residual capacity.

The increase in right atrial transmural pressure was explained on the basis of an increase in pulmonary artery transmural pressure which was observed with increasing PEEP (Scharf et al., 1977) and which was probably due to collapse of the pulmonary microvasculature (Whittenberger et al., 1960). The observed increases in left atrial transmural pressure were less easily explained and form the basis for this study.

We studied the following possible mechanisms to explain the increases in left atrial transmural pressure during PEEP: (1) local increases in pericardial pressure above and beyond those recorded in the pleural space (Brookhard and Boyd, 1947; Wiggers et al., 1947), (2) decreased left ventricular contractile function leading to ventricular dilation (Mahler et al, 1975), and (3) decreases in left ventricular compliance. We studied changes in left ventricular volume, shape, and compliance, and we also examined the relationship between pericardial and pleural pressure as PEEP was applied.

Methods

Mongrel dogs of either sex weighing 18-25 kg, were anesthetized with sodium pentobarbital, 30 mg/kg, iv. Tracheostomy was performed, and mechanical ventilation was begun with a constant vol-
diastolic dimensions were taken as the maximum distance is called the calibration factor, C. End-parent distance measured on the x-ray film to actual photography of a calibrating disc 23 mm in diameter calibration and spherical distortion was made by fluoro.
mensual procedure was repeated. The PEEP was removed, and enough blood volume was withdrawn to keep CO approximately the same as it had been at the previous baseline. The dog was turned on the right side and the experimental procedure was repeated.

Using the same protocol in seven of the dogs, PEEP was applied in the 30° left anterior oblique (LAO) position and in the 30° right anterior oblique (RAO) position. In each of these positions, left ventricular angiography was performed before and during PEEP. Over 3–5 seconds, 10 ml of iodinated contrast medium were injected into the left atrium (three dogs) or into the left ventricle through a catheter placed there via a carotid artery (four dogs). From the angiogram, the systolic and diastolic outlines of the left ventricular cavity were traced and measured using planimetry and left ventricular volume was calculated according to the area-length method (Dodge et al., 1966): \( V = 0.8488 \left( A^2/L \right) C^3 \), where \( V \) is volume, \( A \) is the area measured using planimetry in cm², \( L \) is the distance between the apex and junction of mitral and aortic valves, and \( C \) is the calibration factor. Ejection
fraction was calculated as end-diastolic minus end-systolic volume divided by end-diastolic volume.

At the end of each experiment, the dogs were killed and the position of the beads was checked at autopsy. In the dogs reported in this study, all the intramyocardial beads were located 0.5–1.0 mm from the endocardial surface.

In seven dogs, the pressure measured in the pleural space was compared to that measured in the pericardial space in the following manner. A thoracotomy was performed in the 4th left intercostal space. A 1.5-cm incision was made in the left lateral pericardium and two latex balloons were inserted into the pericardial space. One of these was placed on the posterior and one on the left lateral myocardial surface. The balloons, which were 2 cm long and on the end of fine (1.5-mm internal diameter) polyethylene tubing, were filled with a volume of air (0.2 to 0.4 cc) which previously had been determined to generate no pressure. The pericardial incision then was sutured closed. The thoracotomy was closed in two layers, and a pleural cannula was introduced into the left hemithorax. Measurements of \( P_{pl} \), posterior pericardial pressure (\( P_{pco} \)), and left lateral pericardial pressure (\( P_{w} \)) were compared during diastole at end expiration at end-expiratory pressure = 0, and PEEP = 15 cm H2O.

In seven additional dogs, left ventricular pressure-volume curves were constructed before and during PEEP of 15 cm H2O. The sternum and pericardium were left open wide and cinefluorograms were taken serially in the supine and right lateral positions while Ringer’s lactate was being infused intravenously to raise left atrial transmural pressure. In these dogs, left atrial transmural pressure was assumed to be equal to the measured \( P_{a} \) since the \( P_{pl} \) was zero (open chest). This assumption was tested in four of these dogs by placing the pericardial balloons in the lateral and posterior positions. The maximum rise in pericardial pressure at the levels of PEEP used here was 0.5 mm Hg seen in one dog in the lateral balloon in the supine position.

Statistical analysis was done by Student’s t-test for paired variables. Values are expressed as mean ± standard error of the mean.

**Results**

**Changes in Pulmonary and Cardiovascular Parameters**

The following pressure changes occurred with the application of PEEP. Although, at end-expiratory pressure = 0, the pleural pressures were significantly different (supine = –2.9 ± 0.4 mm Hg; right lateral = –0.8 ± 0.5 mm Hg, \( P < 0.05 \)), \( P_{pl} \) rose by approximately the same amount (supine = +6.5 ± 0.8; right lateral = +5.5 ± 0.6) in the two positions for identical levels of end-expiratory airway pressure (supine = 14.3 ± 0.3 mm Hg; right lateral = 14.7 ± 0.3 mm Hg).

**Table 1 Changes in Hemodynamic Measurements with PEEP (13 Dogs)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>End-expiratory pressure = 0</th>
<th>Change during PEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{a} ) (mm Hg)</td>
<td>88.0 ± 8.0</td>
<td>–8.8 ± 3.3*</td>
</tr>
<tr>
<td>CO (liters/min)</td>
<td>1.96 ± 0.32</td>
<td>–0.06 ± 0.03*</td>
</tr>
<tr>
<td>HR (beats/min)</td>
<td>156 ± 8</td>
<td>–6.7 ± 3.6</td>
</tr>
<tr>
<td>( P_{a} - P_{w} ) at end expiration (mm Hg)</td>
<td>7.0 ± 0.9</td>
<td>+2.5 ± 0.5†</td>
</tr>
</tbody>
</table>

*\( P < 0.02; † P < 0.001.\)

Table 1 shows the hemodynamic variables measured in the supine position. Changes with the dogs in the lateral and oblique positions were similar. There was a small but statistically significant decrease in mean CO and mean arterial blood pressure with PEEP despite volume infusion and an unchanged heart rate. There was a highly significant increase in left atrial transmural pressure (\( P_{a} - P_{w} \)), similar to that observed in previous studies (Scharf et al., 1977).

**Changes in Left Ventricular Volume, Dimensions, and Shape**

Table 2 shows the changes in left ventricular volume and ejection fraction, as measured by angiography. There were no significant changes in end-diastolic volume or ejection fraction in spite of the increase in left atrial transmural pressure seen with PEEP. Table 3 shows the results of the measurements of left ventricular axes and volumes at end diastole measured by the bead technique. There were no statistically significant changes in end-diastolic ventricular axes or volumes. However, we found a small change in left ventricular shape that was not detected by measurements of the axes themselves. Table 4 shows that at end diastole there was a small but significant increase in the ratios \( L_{2}/L_{3} \).
Changes in Pericardial Pressure with PEEP

Table 5 shows the comparison of end-expiratory $P_{pl}$ and pericardial pressures ($P_{p<1}$ and $P_{pi}$) in the supine and right lateral positions. In each position at end-expiratory pressure = 0, pericardial pressures were similar and were significantly higher than the $P_{pl}$. During PEEP there was no significant difference between measurements of pericardial or pleural pressure $P_{pl}$. Thus, pericardial pressures did not increase more with PEEP than did the $P_{pl}$.

Changes in Left Ventricular Diastolic Pressure-Volume Properties

Figure 1 shows that in all seven dogs a shift occurred in the pressure-volume curve such that during PEEP, as compared with end-expiratory pressure = 0, a given diastolic ventricular volume was accompanied by an increase in transmural $P_{m}$. Conversely, at any given transmural $P_{m}$, ventricular volume was less during PEEP than at end-expiratory pressure = 0. We fit the data to an exponential equation the form $P = a e^{bv}$ where $P$ is pressure, $v$ is volume, and $a$ and $b$ are constants (vide infra). Correlation coefficients using an exponential regression were higher than those using a linear regression. Table 6 gives the values of these constants as well as the correlation coefficient, $r$, for each dog. The difference in constant $b$ between PEEP and control (end-expiratory pressure = 0) was significant ($P < 0.05$), whereas the difference in constant $a$ was not.

Table 4 Changes in Ventricular Configuration (Axis Ratios in 13 Dogs)

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Mean ± SE</th>
<th>Change during PEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_2/L_1$</td>
<td>0.44 ± 0.03</td>
<td>+0.05 ± 0.02*</td>
</tr>
<tr>
<td>$L_3/L_1$</td>
<td>0.59 ± 0.07</td>
<td>-0.02 ± 0.02</td>
</tr>
<tr>
<td>$L_3/L_2$</td>
<td>0.76 ± 0.09</td>
<td>+0.08 ± 0.03†</td>
</tr>
</tbody>
</table>

* $P < 0.02$, † $P < 0.01$.

Discussion

The present study shows that the previously described increase in transmural $P_{m}$ with PEEP is demonstrable whether $P_{m}$ is referenced to pericardial pressure or $P_{pl}$. Furthermore, this increase is associated with changes in left ventricular configuration and diastolic pressure-volume curve. The ensuing discussion will consider the basis for these findings and will include a critical assessment of the techniques used in arriving at them.

In previous studies, $P_{m}$ was referenced to $P_{pl}$ and the latter was assumed to represent pericardial pressure adequately. The difficulties in measuring $P_{m}$ changes by techniques similar to those used in these studies have been noted previously (McMahon et al., 1969). A small error in measuring the rise in $P_{m}$ during PEEP could lead to erroneous conclusions. The data from the experiments in which CO was kept relatively constant (Tables 1-4) indicated that, except for a rise in left atrial transmural pressure and a small shape change in the left ventricle, little else changed. Our data demonstrated that with the application of PEEP the rise in pericardial pressure was not greater than the rise in $P_{pl}$, so that previously reported increases in left atrial transmural pressure were valid. The difference in the baseline values measured for pericardial and pleural pressures at end-expiratory pressure = 0 (Table 5) has been noted in the past and may have been related to mechanical interactions between the heart and lung surfaces such as compression of the medial surface of the lungs by the heart (Brookhard and Boyd, 1947; Wiggers et al., 1947). It also may have been related to the introduction of a slight amount of air into the pericardial space producing a small rise in baseline pericardial pressure relative to $P_{pl}$.

Another possible source of measurement error could arise if, during PEEP, the heart was elevated relative to the pressure gauges, thus introducing a hydrostatic artifact in the measurements of intracardiac pressure. In unpublished experiments in three dogs, previously killed by injection of KCl, we ligated the superior and inferior venae cavae, azyg-
The calculation of diastolic ventricular volume by the bead technique was done using data obtained at different times from two different projections. Although use of simultaneous biplane cinefluorography would have been preferable, we believe we are justified in including our calculations here. During diastole, alignment of the beads in the two projections appeared to be adequate since the AP beads most often were superimposed in the AP projection and the septal-lateral beads most often were superimposed in the lateral projection. This indicates that twisting of the heart did not occur due to turning the dogs. Furthermore, there was excellent agreement between the fluorographic and angiographic techniques (Tables 2 and 3) in the calculated diastolic volumes. Systolic dimension and volume calculations based on measurements of the axes are not shown. We believed that they were unreliable because the twisting motion of the heart during systole substantially altered bead alignment from a diastolic configuration that was close to perpendicular to the plane of fluoroscopy.

**Changes in Left Ventricular Function**

Since end-diastolic volumes did not increase with PEEP, an increase in left ventricular preload was not responsible for the observed rise in left atrial

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### Table 6 Parameters for Regression Lines Plotted for Diastolic Pressure-Volume Curves Shown in Figure 1 Assuming P = ae^b

<table>
<thead>
<tr>
<th>Dog</th>
<th>Control</th>
<th>PEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>1</td>
<td>0.008</td>
<td>0.463</td>
</tr>
<tr>
<td>2</td>
<td>0.107</td>
<td>0.223</td>
</tr>
<tr>
<td>3</td>
<td>0.104</td>
<td>0.211</td>
</tr>
<tr>
<td>4</td>
<td>1.083</td>
<td>0.070</td>
</tr>
<tr>
<td>5</td>
<td>0.500</td>
<td>0.100</td>
</tr>
<tr>
<td>6</td>
<td>0.540</td>
<td>0.070</td>
</tr>
<tr>
<td>7</td>
<td>0.090</td>
<td>0.170</td>
</tr>
</tbody>
</table>

Mean 0.350 0.160 0.700 0.990 0.600 0.090 0.16

<table>
<thead>
<tr>
<th>(mm Hg)</th>
<th>(ml)</th>
<th>(mm Hg)</th>
<th>(ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.463</td>
<td>0.070</td>
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<td>0.95</td>
</tr>
</tbody>
</table>

Mean 0.350 0.160 0.700 0.990 0.600 0.090 0.16

Unit for a = mm Hg, units for b = ml⁻¹. P = pressure (mm Hg), v = volume (ml), a = y-intercept (mm Hg), and b = slope of instantaneous stiffness-pressure curve (ml⁻¹). For a, difference between control and PEEP was not significant; for b, difference between control and PEEP was significant (P < 0.06). Correlation coefficient, r, is also shown.
transmural pressure. Furthermore, we found no evidence for a decrease in left ventricular contractile function with PEEP since ejection fraction did not change. This is supported by other studies in which no change in left ventricular maximum dP/dt was found with PEEP (Green et al., 1977).

Changes in Left Ventricular Configuration

The statistically significant changes in the ratios L2/L1 and L2/L3 indicate that a change occurred in ventricular configuration.

The shape of a compliant fluid-filled container such as the left ventricle could be altered by non-uniform changes in the external forces acting on the container and/or by non-uniform changes in the elastic properties of the container, i.e., muscle stiffness. In the present studies, the shape change—probably not due to non-uniform changes acting on the pericardial surfaces of the left ventricle because PEEP induced similar changes in the lateral and posterior pericardial pressures (Table 6). Furthermore, we found a shortening of the apex-base axis (L1) relative to the septal-lateral (L2) which would mean that pressure would have to have increased more in the long axis of the pericardial sac than in the transverse axis. It is difficult to imagine how this could occur with PEEP, since the tendency would be for the descent of the diaphragm to stretch the heart in its long Li axis rather than to compress it.

The left ventricle also shares a surface in common with the right ventricle, i.e., the interventricular septum. In the absence of nonhomogeneous pericardial pressure changes, it seems probable that the explanation for the change in shape of the left ventricle lies in the forces acting on the interventricular septum or in changes in septal stiffness. During PEEP there are increases in both pulmonary artery and right atrial transmural pressures (Scharf et al., 1977) which could lead to dilation and stretching of the right ventricle and changes in left ventricular geometry through ventricular interaction (Bemis et al., 1974; Kelley et al., 1971; Menkes et al., 1974; Moulopoulos et al., 1965; Santamore et al., 1976; Stool et al., 1974; Taylor et al., 1967). This may form the basis for the change in the diastolic pressure-volume curve discussed below.

Changes in the Left Ventricular Pressure-Volume Characteristics with PEEP

The data presented in Tables 1–3 indicate that there was a change in left ventricular diastolic pressure-volume properties with PEEP. This is because, at the same mean left ventricular volume (approximately 20 ml), the mean transmural Pw was 2.5 mm Hg greater with PEEP than without. This suggested a stiffening of the left ventricle. This observation was confirmed by the data presented in Figure 1, which demonstrated a shift in the diastolic pressure-volume curve with PEEP. To analyze these curves quantitatively, we chose to fit them to an exponential equation of the form P = ae\(^{bP}\) since it is generally accepted that, at ventricular filling pressures greater than 3–5 mm Hg, the diastolic pressure-volume curve of the left ventricle fits an exponential equation (Diamond et al., 1971; Gaeth et al., 1972; Grossman and McLaurin, 1976; Mirsky and Parmley, 1973; Mirsky, 1976). Although at the extremes of the curve there are deviations from the exponential form (Glantz, 1976), within the operating range it seems appropriate to use this form, since we found higher correlation coefficients with it than with a linear regression. In the exponential analysis, constant b is the slope of a line relating instantaneous ventricular "stiffness" (dp/dv) to pressure (Diamond et al., 1971), and is independent of absolute values of volume or pressure. Constant b may be thought of as an index of overall ventricular stiffness (Mirsky, 1976). The data presented in Table 6 indicate that this constant increased with PEEP.

Based on the mean values for a and b shown in Table 6, we have constructed "mean" left ventricular diastolic pressure-volume curves for the seven dogs illustrated in Figure 1. These mean curves are shown in Figure 2. Point A on the control curve, at a transmural Pw of 7.0 mm Hg, marks the mean value found in the dogs presented in Table 1. Point B on the PEEP curve corresponds to an increase in transmural Pw of 2.5 mm Hg, the mean increase found in the dogs presented in Table 1. It can be seen that essentially no volume change would have been expected for this increase in transmural Pw with PEEP, and indeed this was the case (Tables 2 and 3). Thus, our findings of increased transmural Pw and no change in left ventricular volume, appear to be explained by changes in the left ventricular pressure-volume curves.

It is known that filling of the right ventricle can alter the diastolic pressure-volume curve of the left ventricle in a manner resembling that illustrated in...
Figure 2 (Laks et al., 1967; Stool et al., 1974; Taylor et al., 1967). The same forces (discussed above) which act during PEEP to change the shape of the left ventricle may also act to change its pressure-volume curve.

In sum, the increase in left atrial transmural pressure seen with PEEP was adequately explained by a shift of the left ventricular diastolic pressure-volume curve in the direction of a stiffer left ventricle. No evidence was found for a decrease in left ventricular contractile function with PEEP. We suggest that the observed changes in left ventricular shape and stiffness were due to the effects of PEEP on the right ventricle, and ventricular interdependence.

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