Liver and Ductus Venosus Blood Flows in Fetal Lambs in Utero

DANIEL I. EDELSTONE, ABRAHAM M. RUDOLPH, AND MICHAEL A. HEYMANN

SUMMARY We evaluated the circulation of the liver and ductus venosus, using the radionuclide-labeled microsphere technique, in 24 chronically prepared fetal lambs. We placed catheters in fetal descending aorta and inferior vena cava, and in a carotid artery and an umbilical vein; in 11 fetuses, we also inserted a catheter in a mesenteric vein that drained into the portal vein. After allowing 2-4 days for recovery from the stresses of anesthesia and operation, we measured blood flow to the fetal liver and its various lobes and through the ductus venous. Total blood flow to the liver was 435 ± 122 ml/min per 100 g liver (mean ± SD), of which hepatic arterial flow represented 9%, portal venous flow 18%, and umbilical venous flow 73%. Hematic arterial and umbilical venous flows were approximately equally divided between left and right lobes, although portal blood flow was directed almost exclusively to the right lobe. The right lobe received 40% more total blood flow than the left, even though the left lobe weighed more than the right. Approximately 53% of umbilical venous blood flow but less than 9% of portal venous blood flow entered the ductus venosus; umbilical venous flow therefore accounted for more than 98% of ductus venous blood flow. Ductus venosus flow showed a strong linear correlation with umbilical blood flow. However, there was no relationship between ductus venosus flow and gestational age. The results suggest that the liver receives a large blood flow primarily because of a large umbilical venous contribution. It is not clear whether the hepatic arterial and portal vessels, the ductus venosus gives no branches to the liver. Three investigators have measured the proportion of umbilical and portal venous blood that flows through the ductus venosus. In acute experiments on anesthetized fetuses of sheep, humans, and rhesus monkeys, the portion of umbilical venous blood that entered the ductus venosus varied considerably. In anesthetized fetal lambs, Amoroso et al. showed that little, if any, portal blood passes through the ductus venosus. All of these studies, however, were performed on fetuses subjected to the acute influences of anesthesia and operation, two factors known to affect umbilical blood flow. Therefore, these studies may not reflect what takes place in the undisturbed fetus in utero.

In this report, we define the normal blood flow to the fetal liver and through the ductus venosus in chronically prepared, unanesthetized fetal lambs. We determine the relationship between ductus venosus blood flow and umbilical blood flow and between ductus venosus flow and gestational age.

Methods

Preparation of Animals

We studied 24 fetal lambs with time-dated gestational ages of 116-136 days. After spinal or epidural anesthesia was induced with 1% tetracaine hydrochloride, we placed polyvinyl catheters into branches of a maternal femoral artery and vein. We opened the maternal abdomen and uterine horn, and placed catheters into a fetal hind limb.
artery and vein. These catheters were advanced to descending aorta and inferior vena cava, respectively. We placed a catheter in a cotyledonary branch of the umbilical vein in the horn of the uterus and advanced the catheter 10-12 cm so that the tip was in a main umbilical vein. In 14 of the 24 fetuses, we inserted a catheter in a carotid artery. In 11 of the 24 fetuses, we also placed a catheter in a small mesenteric vein in the following manner. We made a 3-cm incision in the left lower quadrant of the fetal abdomen and fixed the cut skin edges to the uterine muscle and amniotic membrane to prevent loss of amniotic fluid. After entering the peritoneal cavity and withdrawing several loops of small bowel, we located a vein within the vascular arcade that supplies the gut. We inserted a polyvinyl catheter (0.015-inch i.d., 0.035-inch o.d.) and advanced it approximately 5 cm so that the catheter tip was directed toward the portal vein. After closing the fetal abdomen, we placed a catheter in the amniotic sac, closed the uterine incision, and brought the catheters out subcutaneously to the ewe’s flank. Postoperatively, each ewe received penicillin and kanamycin intravenously and intramuscularly for 2 days. Vascular catheters were flushed with heparin daily to ensure catheter patency. Two to four days after surgery, we studied the fetuses of the unanesthetized ewes. We studied only fetuses with normal descending aortic blood gases (pH ≥ 7.35, Po2 ≥ 20 torr, Pco2 ≤ 45 torr). We measured blood flows with 15 μm in diameter radionuclide-labeled microspheres and arterial blood references samples.

Blood Flow to Liver and Through Ductus Venosus

In the 11 fetuses with portal vein catheters, we determined blood flow and its distribution to the fetal liver, as well as portal and umbilical venous blood flow through the ductus venous. We measured blood pressure in descending aorta, inferior vena cava, portal vein, and umbilical vein, amniotic fluid pressure, and fetal heart rate for at least 30 minutes. When these were stable, 1 ml of blood was withdrawn from each vascular catheter to measure blood gases. A complete set of measurements of blood gases was obtained in only seven instances. We injected 15-μm microspheres, labeled with different radionuclides, simultaneously into the inferior vena cava, portal, and umbilical venous catheters, while obtaining a descending arterial blood reference sample (and carotid arterial sample in those fetuses with a carotid arterial catheter).

Serial Studies of Ductus Venosus Blood Flow

It was apparent after a few studies that portal blood flow through the ductus venosus was small and that umbilical venous blood contributed almost all of the flow through the ductus venosus. Since we also wanted to evaluate ductus venosus flow serially through gestation, we determined only the umbilical venous contribution to blood flow through the ductus venosus in an additional 11 fetuses. In four of these, we injected microspheres, labeled with different radionuclides, into the umbilical venous catheter 2-4 times during a single day to assess diurnal variation. In three fetuses, microspheres were injected into the umbilical vein daily for 2-3 days to determine any daily variations in ductus venosus flow. In the remaining four fetuses, we injected microspheres into the umbilical vein at 3- to 6-day intervals beginning at 118-128 days gestation and progressing toward term (147 days) to evaluate ductus venosus flow during the last 3 weeks of gestation. To calculate blood flow per kilogram of fetal body weight in these latter four growing fetuses, we estimated fetal weight from gestational age, using the data of Barcroft. Prior to each microsphere injection, we measured descending aortic, inferior vena cava, and umbilical venous blood pressures, amniotic fluid pressure, and fetal heart rate for at least 30 minutes. When these were stable, 1 ml of blood was obtained from each vascular catheter for evaluation of blood gases. During microsphere injections, descending aortic (and carotid arterial, where available) blood reference samples were withdrawn to calculate actual blood flows. The volume of blood removed was replaced with maternal arterial blood.

Measurements of Pressures, Heart Rate, and Blood Gases

We measured all pressures with Statham P23Db pressure transducers and heart rate with a cardiotachometer triggered by the fetal arterial pressure pulse, and recorded these on a Beckman direct-writing recorder. Mean blood pressures were obtained electronically. Blood gases (pH, Po2, and Pco2) were measured with standard electrodes and a blood gas meter (Radiometer).

Preparation of Tissues

Upon completion of each study, ewes were killed with sodium pentobarbital and potassium chloride, and the entire uterus and its contents were removed. Each fetus was dissected in a uniform manner and all animal tissues were analyzed. We divided the fetal liver into left, right, and caudate lobes. The line of demarcation between left and right lobes extends between the fossae of the inferior vena cava and the gall bladder. This line is just to the right of the ductus venosus. A small portion of
the caudate lobe\(^5\) lies to the left of this line; since it was
difficult to determine how much of this tissue was caudate
lobe, we included this part with the left lobe. The remain-
der of the caudate lobe was dissected and evaluated
separately.

The fetal organs, carcass, and placenta were processed
as previously described.\(^8\) The amounts of each nuclide in
each tissue sample were measured with a well-type gamma
scintillation counter and a 512-channel pulse-height ana-
lyzer (Searle Analytical Co.).

Calculation of blood flow to fetal organs (excluding liver),
carcass, and placenta (umbilical blood flow) were
performed by computer (IBM 360). Our methods for
calculating blood flow to the liver and through the ductus
venosus are given in the Appendix. We calculated cardiac
output, using descending aortic and carotid arterial blood
reference samples.\(^8\) When only descending aortic blood
reference samples were available, cardiac output was
approximated by methods described previously.\(^8\) We used
the paired $t$-test and linear regression analyses to analyze
our data statistically.\(^10\)

**Results**

**Quantification of Arteriovenous and Veno-Venous
Shunts in the Liver**

We selected microspheres 15 $\mu$m in diameter, since
larger ones obstruct a greater proportion of the microcircu-
lation. However, several anatomic studies in fetal lambs have shown that liver sinusoids are approximately
12–15 $\mu$m in diameter.\(^11\)\(^-\)\(^12\) These studies have also
described hepatic artery-hepatic vein anastomoses (10–20
$\mu$m in diameter) and umbilical or portal vein-hepatic vein
anastomoses (approximately 30 $\mu$m in diameter), but they
have not noted hepatic artery-portal vein connections.\(^12\)

Therefore, to determine (1) whether the sinusoids of the
fetal liver trap 15–$\mu$m microspheres and (2) how much, if
any arteriovenous or veno-venous shunting exists, we
simultaneously injected 50- and 15-$\mu$m microspheres with
different radionuclide labels into the umbilical vein and
into the inferior vena cava of the two remaining fetuses.
There were no significant differences between distribution of
50-and 15-$\mu$m microspheres to the whole liver or to the
left, right, or caudate lobes. This demonstrated that (1)
microspheres of 15-$\mu$m diameter are trapped by the
sinusoids of the fetal liver and (2) there is little arteriove-
 nous or veno-venous shunting in blood vessels of less than
50-$\mu$m diameter in the fetal liver.

**Blood Respiratory Gases and Vascular Pressures**

Table 1 shows blood respiratory gases and mean arterial
and venous blood pressures. We found no significant
differences between inferior vena caval and portal venous
blood gases. We also found no consistent differences
between portal and umbilical venous mean blood pres-
"
Table 3  Blood Flow to the Liver, Supplied by the Hepatic Artery, Portal Vein, and Umbilical Vein, in Normal Fetal Lambs in Utero

<table>
<thead>
<tr>
<th></th>
<th>Left lobe</th>
<th>Right lobe</th>
<th>Caudate lobe</th>
<th>Whole liver</th>
<th>Percent of combined ventricular output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hepatic artery (ml • min⁻¹) (ml • min⁻¹ • 100 g⁻¹)</td>
<td>9 ± 15</td>
<td>18 ± 26</td>
<td>1 ± 1</td>
<td>28 ± 40</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>23 ± 34</td>
<td>54 ± 68</td>
<td>18 ± 12</td>
<td>36 ± 45</td>
<td></td>
</tr>
<tr>
<td>Portal vein (ml • min⁻¹) (ml • min⁻¹ • 100 g⁻¹)</td>
<td>1 ± 2</td>
<td>43 ± 20</td>
<td>13 ± 9</td>
<td>57 ± 21</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>4 ± 6</td>
<td>138 ± 50</td>
<td>256 ± 163</td>
<td>80 ± 25</td>
<td></td>
</tr>
<tr>
<td>Umbilical vein (ml • min⁻¹) (ml • min⁻¹ • 100 g⁻¹)</td>
<td>116 ± 33</td>
<td>100 ± 64</td>
<td>14 ± 9</td>
<td>230 ± 71</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>329 ± 124</td>
<td>306 ± 140</td>
<td>290 ± 169</td>
<td>319 ± 95</td>
<td></td>
</tr>
<tr>
<td>Total (ml • min⁻¹)</td>
<td>126 ± 46</td>
<td>161 ± 78</td>
<td>28 ± 12</td>
<td>315 ± 92</td>
<td>24.7</td>
</tr>
<tr>
<td></td>
<td>356 ± 129</td>
<td>498 ± 150</td>
<td>564 ± 175</td>
<td>435 ± 122</td>
<td></td>
</tr>
</tbody>
</table>

n = 11; values are mean ± SD.

Ductus venosus blood flow showed no consistent trend in the four fetuses in which we measured it 2–4 times in a single day. When we evaluated ductus venous flow (per kilogram of fetal weight) as a function of gestational age, we could find no correlation in either the series of 15 fetuses in which we measured flow on a single day only (11 fetuses with portal venous catheters, and in the first study in four fetuses in which flow was determined 2–4 times in a single day) or in the series of seven fetuses in which we determined ductus flow either at daily intervals (three fetuses) or at 3- to 6-day intervals (four fetuses). Ductus venosus blood flow per unit weight, however, correlated closely with umbilical blood flow per unit weight (Fig., 4A and B) even though the proportion of umbilical venous return to the fetus that entered the ductus venosus showed no relationship to umbilical blood flow.
The large umbilical venous contribution to the right and caudate lobes almost exclusively; this is consistent both with the anatomical arrangement of the portal venous circulations within the portal sinus. Our finding that almost half of the umbilical venous blood flow to the fetal liver supplies the right side disagrees with cineangiographic observations on anesthetized fetal lambs that umbilical venous blood crosses the portal sinus but does not enter the parenchyma of the right lobe. The use of anesthetic agents may have influenced those cineangiographic results. The demonstration of a large umbilical flow to the right lobe makes it difficult to understand why fetal asphyxia affects the right lobe more than the left lobe. It is possible that the right and left lobes react differently to asphyxic stress.

There are some quantitative similarities between the circulation of the liver of fetal and adult sheep. In adult ewes, hepatic arterial flow to the whole liver is extremely small, approximately 2 ml/min per 100 g liver. Total portal blood flow is approximately 100-150 ml/min per 100 g liver. Therefore, total flow to the liver of adult sheep is similar to the total of hepatic arterial and portal venous flows that we have obtained in fetal lambs (116 ml/min per 100 g liver). The fact that portal blood flow accounts for over 95% of total liver flow in adult sheep is very different from studies in adult dogs or humans where portal blood flow contributes only about 60-75% of the total. The reason for this difference may be related to the peculiarities of the sheep's four-chambered digestive system. The major difference in the magnitude of liver blood flow between adult and fetal sheep is the umbilical venous supply to the fetal liver.

Ductus Venosus Blood Flow

The function of the ductus venosus remains unclear at present. In some species (horse, pig), the ductus is obliterated very early in fetal development, yet in most species it is patent until after delivery. It may function to ensure an adequate venous return to the fetal heart when umbilical venous return fluctuates. Chacko and Reynolds and Dickson have suggested that the ductus venosus modulates umbilical and portal venous blood pressures to maintain an equilibrium between them for proper flow relationships in the liver and ductus venosus. Ductus venosus blood flow would therefore be related to pressures in the umbilical and portal circulations. Although we noted that umbilical and portal venous blood pressures were approximately equal, which would support this con-
cept, we were unable to correlate ductus venosus blood flow with umbilical or portal venous pressure or umbilical-portal venous pressure differences. In addition, there was no obvious relationship of ductus venosus flow to total or lobar liver flows. Thus it is unlikely that the ductus changes its caliber and therefore its resistance to maintain a stable blood flow to the liver.

In our studies, the proportion of umbilical venous blood flow that passed through the ductus venosus varied within a more narrow range (36-64%) than has been reported previously in acute experiments on fetal sheep (34-91%).3 Human fetuses (8-92%), and fetal rhesus monkeys (30-71%).6 This large variability could be because those studies were performed on fetuses that were subjected to the acute influences of anesthetic and operative stresses. In sheep3 and human4 fetuses, larger umbilical venous blood flows were associated with a higher proportion of umbilical venous flow through the ductus venosus. Studies on fetal rhesus monkeys4 showed the opposite result; i.e., larger umbilical venous flows were associated with a smaller proportion of umbilical flow through the ductus. We were unable to show a relationship between that portion of umbilical venous return to the fetus that passes through the ductus and umbilical venous blood flow. Nor could we demonstrate an association between ductus venosus blood flow, corrected for fetal body weight, and gestational age. Nevertheless, the linear relationship between ductus venosus blood flow (per unit fetal weight) and umbilical blood flow (per unit fetal weight) suggests that, at least within the normal range for umbilical flow, the ductus venosus acts passively.

Our observation on undisturbed fetal lambs in utero that less than 10% of portal venous blood flow reaches the ductus venosus supports Amoroso et al.7 who analyzed the oxygen content of blood samples from portal vein, umbilical vein, and ductus venosus of anesthetized fetal lambs. They concluded that little, if any, portal blood enters the ductus. This also is consistent with our finding that more than 98% of ductus venosus blood is derived from umbilical venous blood.

It would be of additional interest to study the normal circulatory patterns of the newborn liver to determine when its circulation assumes that of the adult liver. Since the umbilical circulation ceases after birth, the major blood supply of the liver, and of the left lobe in particular, must come from the portal vein. Emery41 has shown that, in the presence of asphyxia in human newborns, the left lobe of the liver is particularly sensitive to degenerative changes, a finding that he relates to the sudden cessation of highly oxygenated umbilical venous blood and its replacement with poorly oxygenated portal venous blood.

In conclusion, we have determined the normal blood flow and its distribution to the fetal liver and ductus venosus in unanesthetized fetal lambs in utero. Blood flow to the liver is high, primarily because of a large umbilical venous blood flow. The question then arises, is this extremely large blood flow (and oxygen delivery) necessary for normal liver function and growth? In adult sheep, dog, and man, oxygen consumption by the liver is high (2-7 ml Q/min per 100 g liver).18 It is not known what comparable values in the fetus are, but it is possible that specialized functions of the fetal liver, e.g., hematopoiesis, iron storage, steroid synthesis and metabolism, require a large blood flow and oxygen delivery. It also is not known whether or not each lobe of the liver receives its particular flow pattern because of certain unique functions that each lobe performs.5 If so, this could explain why the right lobe, which is smaller than the left one in fetal life, receives a much larger flow than the left lobe. This same phenomenon has been observed in adult sheep as well.22

It would be important to determine what effect asphyxia, with its resultant fetal hypoxemia and decreased umbilical blood flow, has on blood flow to the fetal liver and ductus venosus. We have preliminary studies that show that large decreases in umbilical blood flow produce decreases in total flow to the liver with a more striking reduction of flow in the right than in the left lobe. These studies suggest that perfusion of the left lobe by umbilical venous blood may be maintained at the expense of the right lobe. Furthermore, ductus venosus blood flow decreases linearly with reductions in umbilical blood flow. These findings could have important consequences in instances where umbilical flow decreases in response to fetal stress.

Appendix

Abbreviations

\[
\begin{align*}
Q_{H_L} &= \text{hepatic arterial blood flow to the liver} \\
Q_{PV} &= \text{portal venous blood flow (total)} \\
Q_{PV_D} &= \text{portal blood flow to the liver} \\
Q_{PV_DV} &= \text{portal blood flow through the ductus venosus} \\
Q_{U} &= \text{umbilical venous blood flow (total)} \\
Q_{UV} &= \text{umbilical venous blood flow to the liver} \\
Q_{PV} &= \text{portal blood flow through the ductus venosus} \\
Q_{QUV} &= \text{blood flow in descending aortic blood reference sample} \\
Q_{UV} &= \text{blood flow through the ductus venosus (total)} \\
\end{align*}
\]

Other subscripts (in parentheses)

\[
\begin{align*}
(IVC) &= \text{derived from microspheres injected in inferior vena cava} \\
(PV) &= \text{derived from microspheres injected in portal vein} \\
(UV) &= \text{derived from microspheres injected in umbilical vein} \\
\end{align*}
\]

CPM = radioactivity, counts per minute, in an organ or reference (ref) sample

Liver Blood Flow Calculations

1. Hepatic arterial blood flow to the liver: \(Q_{H_L}\) is calculated from (a) injection of microspheres in inferior vena cava (IVC), and (b) descending aortic blood reference sample.

\[
Q_{H_L} = \left( \frac{Q_{QUV} \times CPM_{\text{Liver (IVC)}}}{CPM_{\text{Ref (IVC)}}} \right)
\]
2. Portal venous blood flow to the liver: $Q_{PV}$ is calculated from (a) injection of microspheres in inferior vena cava (IVC), (b) injection of microspheres in portal vein (PV), and (c) descending aortic blood reference sample.

$$Q_{PV} = Q_{PV} - Q_{PV,DV}$$

$$Q_{PV} = Q_{IVC} + Q_{spleen} + Q_{bypass}$$

and

$$Q_{PV,L} = Q_{PV} \left( \frac{CPM_{liver}(UV)}{CPM_{fetus} + placenta (IVC)} \right)$$

A small error is introduced in these calculations by not including the recirculation of microspheres injected into the portal vein that enter the ductus venosus rather than the liver, are returned to the heart, and reach the liver subsequently via the hepatic artery. This error is quite small (less than 2%), since $Q_{PV,DV}$ is usually less than 10% of $Q_{PV}$. $Q_{bypass}$ is rarely larger than 60 ml/min, and the fraction, $CPM_{liver}(UV)/CPM_{fetus} + placenta (IVC)$, is generally less than 2%.

A second small error is present in calculation of total portal venous drainage. $Q_{PV}$ actually includes some rectal blood flow that drains into hemorrhoidal veins rather than mesenteric veins.

3. Umbilical blood flow to the liver: $Q_{U}$ is calculated from (a) injection of microspheres in inferior vena cava (IVC), (b) injection of microspheres in umbilical vein (UV), and (c) descending aortic blood reference sample.

$$Q_{U} = Q_{U} - Q_{UV}$$

$$Q_{U} = \left( \frac{Q_{U} + CPM_{placenta} (IVC)}{CPM_{fetus} + placenta (IVC)} \right)$$

$$Q_{U,L} = Q_{U} \left( \frac{CPM_{liver} (UV)}{CPM_{fetus} + placenta (UV)} \right)$$

but $CPM_{liver} (UV)$ is not directly available. Total $CPM_{liver} (UV)$ (sum of $CPM_{UV}$ of microspheres that are trapped by liver on first circulation plus proportion of $CPM_{UV}$ of microspheres that bypass the liver through the ductus venosus, reach the heart, and then are distributed to the liver via the hepatic artery) is actually measured. $CPM_{liver} (UV)$ represents microspheres that are trapped on the first circulation only and is calculated as follows:

$$CPM_{liver} (UV) = CPM_{liver} (UV) - \left( \frac{CPM_{fetus} + placenta (IVC)}{CPM_{fetus} + placenta (IVC)} \right) CPM_{liver} (UV)$$

solving for $CPM_{liver} (UV)$:

$$CPM_{liver} (UV) = \left[ \frac{CPM_{liver} (UV)}{1 + \left( \frac{CPM_{liver} (UV)}{CPM_{fetus} + placenta (IVC)} \right)} \right]$$

and

$$Q_{U,L} = Q_{U} \left( \frac{CPM_{liver} (UV)}{CPM_{fetus} + placenta (UV)} \right)$$

For blood flow to a particular lobe of the liver, $CPM$ for that lobe is substituted for $CPM_{liver}$ for both (UV) and (IVC).

**Ductus Venosus Blood Flow Calculations**

1. Actual ductus venosus blood flow is calculated from the sum of the components:

$$Q_{DV} = Q_{UV} + Q_{PV,DV}$$

$$Q_{UV} = Q_{U} - Q_{U,L}$$

and

$$Q_{PV,DV} = Q_{PV} - Q_{PV,L}$$

2. When both portal venous (PV) and inferior vena caval (IVC) injections of microspheres are not available:

$$Q_{UV} = Q_{U} \left[ 1 - \left( \frac{CPM_{liver} (UV)}{CPM_{fetus} + placenta (UV)} \right) \right]$$

This introduces a maximum potential error of 6%. This error is only this large when 60% of the umbilical vein injection of microspheres enters the ductus venosus (rather than the liver), and 10% of this returns to the liver via the hepatic artery (which was present in only 1 of 11 fetuses).

**Acknowledgments**

We thank Bruce D. Payne, Carl McWatters, and Christine Roman for their skillful technical assistance.

**References**

The Pericardium Substantially Affects the Left Ventricular Diastolic Pressure-Volume Relationship in the Dog

STANTON A. GLANTZ, GREGORY A. MISBACH, WILLIAM Y. MOORES, DETLEF G. MATHEY, JON LEKVEN, DAVID F. STOWE, WILLIAM W. PARMLEY, JOHN V. TYBERG

SUMMARY We instrumented six dog hearts in vivo to study the relationship between left and right ventricular diastolic pressures with the pericardium closed and open. We measured left ventricular septum-to-free wall and anterior-posterior and right ventricular septum-to-free wall dimensions with implanted ultrasonic crystals, together with simultaneous high fidelity pressures. We varied diastolic pressure by infusing or withdrawing blood or by increasing right ventricular afterload with transient pulmonary artery constriction. Although left and right ventricular diastolic pressures always correlated, this correlation was significantly higher with the pericardium closed than open.

We fit left ventricular diastolic pressure to an equation which included first order right ventricular pressure and fourth order left ventricular dimension terms. With the pericardium closed, the right ventricular pressure term dominated; with the pericardium open, left ventricular dimension terms dominated. Therefore, with the pericardium closed, right ventricular pressure was a more powerful predictor of left ventricular pressure than were left ventricular dimensions in addition, the left ventricle appears much more compliant with the pericardium open. These results led us to modify the traditional view of the diastolic left ventricle as an unconstrained elastic shell of myocardium and replace it with a concept of the diastolic heart as a composite shell of stiff pericardium and compliant muscle, divided into subcompartments (ventricles) by the relatively compliant septum. The influence of the pericardium on the diastolic pressure-volume relationship should be considered in experiments on animals and patient management when the pericardium is open or closed.
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