Lung Water and Urea Indicator Dilution Studies in Cardiac Surgery Patients
Comparisons of Measurements in Aortocoronary Bypass and Mitral Valve Replacement

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SUMMARY We measured transpulmonary indicator dilution curves of Cr-erythrocytes, 131I-albumin, 14C-urea, and 3H-water before and six and 24 hours after operation in seven patients undergoing aortocoronary bypass (ACB) and eight patients undergoing mitral valve replacement (MVR). We calculated cardiac output (CO), extravascular lung water (EVLW), the difference between 131I-albumin and 14C-erythrocyte distribution volumes (EV albumin), the difference between 14C-urea and 14C-erythrocyte distribution volumes (EV urea) and 14C-urea extraction (E) and permeability-surface area (PS) products. Comparisons between 16 ACB studies and 17 MVR studies showed the MVR group to have a higher EVLW (P < 0.01). Extravascular lung water decreased after operation. The ratio of EV urea to EV albumin averaged 1.35 in the MVR group and 0.91 in the ACB group (P < 0.001). 14C-urea E was also higher in the MVR group (P < 0.05), but PS was similar in the two groups. None of the differences was related to the time the studies were done. We showed that EVLW, calculated using both 131I-albumin and 14C-erythrocytes as intravascular indicators and measured blood water content, had a constant relationship to EVLW calculated using only 131I-albumin as the intravascular indicator and neglecting blood water content, over a broad range of cardiac outputs, hematocrits, and lung water volumes. We conclude that patients with mitral valve disease have an increased distribution volume and E for urea, probably due to hemodynamic changes but possibly due to increased vascular permeability. Extravascular lung water decreases after cardiac surgery regardless of the type of operation. A single intravascular indicator is adequate for estimating extravascular lung water in humans.

SEVERAL CLINICAL SYNDROMES characterized by respiratory distress and pulmonary edema are thought to result from increased leakage of lung exchanging vessels.1 2 A technique capable of detecting increased lung vascular permeability in living humans could contribute substantially to understanding the relationship of this abnormality to lung disease.

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Indicator dilution techniques have been used to measure lung water content4 6 and to assess vascular permeability.7 11 Such techniques are attractive because they are not difficult and could provide a simultaneous estimate of both the amount of water in the lung and the leakiness of the microvessels.
Animal studies suggest that both labeled red cells and a plasma tag should be used as intravascular indicators when lung water is measured by indicator dilution,12 13 but most human measurements have been done with only a plasma tag.
To determine the importance of using both a red cell and a plasma label as intravascular indicators in estimating lung water content, and to test the feasibility of using indicator methods to evaluate lung vascular integrity, we measured indicator dilution curves for 14Cr-erythrocytes, 131I-albumin,
\(^{14}\)C-urea and \(^{3}H\)-water across the pulmonary circulation during the perioperative period in one group of patients undergoing aortocoronary bypass and another group undergoing mitral valve replacement.

**Methods**

We studied seven patients undergoing aortocoronary bypass for arteriosclerotic coronary disease and eight patients undergoing prosthetic mitral valve replacement for either mitral stenosis, insufficiency or both. Patients less than 20 years old were excluded from consideration. Informed consent was required, but no other selection criteria were imposed.

Anesthesia was induced with 1–1.5 mg/kg morphine sulfate and 200–250 mg sodium pentobarbital given intravenously and patients were intubated and ventilated with 50% nitrous oxide. Fluothane, 0.5–1%, was given during the operation only when systolic blood pressure was greater than 150 torr. Extracorporeal circulation was maintained with a nonocclusive roller pump and a bubble oxygenator (Temptrol R). The prime consisted of 2000 ml of Ringer's lactate solution and 500 ml of blood in acid-citrate-dextrose solution. Perfusion rates averaged 2.21 L/min \(\times m^2\) body surface area. During cardiopulmonary bypass, the lungs were kept inflated at 5–10 torr inflation pressure with 100% oxygen. During extracorporeal circulation body temperature was reduced to 30°C by a heat exchanger in the arterial circuit and rewarming was completed prior to discontinuing bypass. Three studies were attempted in each patient at specific times before and after operation. The first study was done in the operating room, after the patient was anesthetized, but before the skin was incised. The second and third studies were done six hours and 24 hours respectively after the operation was completed. All patients were mechanically ventilated with a positive pressure ventilator during the preoperative and six hour postoperative studies. The studies at 24 hours after surgery were done with an endotracheal tube in place but with the patient breathing spontaneously.

We used four radioactively labeled indicators. Intravascular indicators were \(^{51}\)Cr-erythrocytes, and \(^{125}\)I-albumin. \(^{14}\)C-urea was used as a permeability indicator and \(^{3}H\)-water was used to estimate lung water content. \(^{51}\)Cr-erythrocytes were prepared by incubating 15 ml of the patient's blood anticoagulated with acid-citrate-dextrose solution overnight with 3052 \(^{51}\)Cr-chromate. Less than 10% of the label remained in the supernatant. Immediately before each study, 10 \(\mu\)Ci \(^{125}\)I-human serum albumin, 40 \(\mu\)Ci \(^{14}\)C-urea and 45 \(\mu\)Ci \(^{3}H\)-water were added to 5 ml of the labeled blood. For each study, we injected 30 ml of the radioactive mixture as a bolus through a central venous catheter and collected 30 arterial blood samples at 1.5 sec intervals by allowing blood to flow from a radial artery catheter (catheter volume = 0.2 ml) into heparinized tubes on a precisely timed rotating disc. We measured radioactivity in 0.5 ml aliquots of each blood sample and in 0.5 ml aliquots of the injected mixture diluted 1/51 in the patient's blood drawn before the study. \(^{51}\)Cr and \(^{125}\)I activity were measured in a gamma scintillation spectrometer (Packard Tricarb Model 3002, Packard Instrument Co., Downers Grove, Illinois), and after ethanol precipita-

tion, \(^{3}H\) and \(^{14}\)C activity were measured in a liquid scintillation spectrometer (Packard Tricarb Model 1312, Packard Instrument Co., Downers Grove, Illinois). We corrected for overlap of \(^{51}\)Cr into \(^{125}\)I and of \(^{14}\)C into \(^{3}H\).

We plotted the radioactivity for each indicator in each arterial blood sample relative to the activity of the indicator injected on a log scale against time after injection on a linear scale and extrapolated the down slopes linearly. Cardiac output was calculated as the inverse of the area under the \(^{51}\)Cr curve. Mean transit times for each indicator were calculated as described by Chinard, Enns, and Nolan. A composite intravascular mean transit time of \(^{51}\)Cr-erythrocytes and \(^{125}\)I-albumin was calculated by the formulas of Goresky, Cronin, and Wangel using \(^{51}\)Cr-erythrocytes and \(^{125}\)I-albumin. These calculations are identical to those previously described. We calculated \(^{14}\)C-urea extraction and permeability-surface area products by the formulas of Crone using the differences between urea and a composite intravascular curve from appearance to the peak of the curves. The composite intravascular curve was calculated from \(^{125}\)I-albumin and \(^{51}\)Cr-erythrocyte values by the formulas of Goresky and associates.

To determine the effect of assuming a constant blood and plasma water content on the extravascular water calculation, we measured the fractional water content of whole blood and plasma in each of 19 studies. In these studies, we collected a sample of blood just prior to indicator injection and determined the water content by drying aliquots of whole blood and plasma to constant weight in a 70°C oven.

Serial measurements in the same patients were compared using a paired \(t\)-test and measurements between groups were compared using a \(t\)-test for independent groups.

**Results**

The numbers of successful studies in each group at each study time were similar in the two groups as shown in table 1. Figure 1 shows preoperative and six hour postoperative studies in one patient undergoing aortocoronary bypass and in one patient undergoing mitral valve replacement. The

**Table 1. Time and Number of Studies in Each Group**

<table>
<thead>
<tr>
<th>Study group</th>
<th>N</th>
<th>Total</th>
<th>Preop</th>
<th>6 hrs postop</th>
<th>24 hrs postop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortocoronary bypass</td>
<td>7</td>
<td>16</td>
<td>7</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Mitral valve replacement</td>
<td>8</td>
<td>17</td>
<td>7</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

\(N = \) number of patients.
curves are typical of those in other patients. In aortocor-
nary bypass patients, the "C-urea indicator curve fell
between the curves for 51Cr-erythrocytes and 125I-albumin,
while in mitral valve replacement patients, the "C-urea peak
was lower than that of albumin, and the downslope was
slower than for either extravascular indicator. Pre- and post-
operative studies were similar in both groups.

Tables 2 and 3 summarize patient data, clinical cardiac
status, cardiopulmonary bypass time, and indicator dilution
results in the two study groups. Age and cardiopulmonary
bypass time were not significantly different between the
groups, but body weight was significantly less in the mitral
valve replacement group (P < 0.05). Half of the mitral valve
replacement patients were women while all of the aorto-
coronary bypass patients were men. Patients in the mitral
group were more symptomatic. Recovery of 14C and 3H was
less than that of 51Cr and 125I in both groups, but recoveries
for all of the indicators were similar for the two groups.

Figure 2 compares cardiac output, extravascular lung
water, and the ratio of excess urea volume to excess albumin
volume in the 16 studies in aortocoronary bypass patients
with the results in the 17 studies in patients who had mitral
valve replacement. As expected from their clinical cardiac
status, extravascular lung water was significantly higher in
the mitral valve replacement group. The ratio of excess urea
volume to excess albumin volume averaged 0.91 in the aor-
tocoronary bypass group and 1.35 in the mitral valve
replacement group. The difference was significant.

Figure 3 compares cardiac output between the groups at
each study time. Although cardiac output tended to be lower
at all study times in the group with mitral valve surgery,
differences between groups were not significant. Extravas-
cular lung water volumes are compared between the groups
at each study time in figure 4. The mean value was higher in
the mitral group at all study times, and the measurement
was much more variable in this group than in aortocoro-
nary bypass patients. Extravascular lung water was
significantly lower than preoperative values at both six hours
(P < 0.05) and 24 hours (P < 0.05) after surgery in the aor-
tocoronary bypass group, and was lower than preoperative
values in all but one of the mitral valve replacement patients
at six hours after surgery.

The ratio of excess urea volume to excess albumin volume
is shown for each study time in figure 5. The ratio con-
sistently averaged less than 1.0 in the aortocoronary bypass
group and greater than 1.0 in the mitral group. The variabil-
ity of this value was large in the latter group, espe-
cially in the preoperative studies. The difference between
the groups was significant before (P < 0.05) and six hours
after (P < 0.05) surgery.

There were no significant differences between pre- and
postoperative 14C-urea extractions and permeability-surface
area (PS) products in either study group. Table 4 sum-
marizes these values for both groups. As illustrated in the
representative curves shown in figure 1, 14C urea extraction
was significantly higher in the mitral valve replacement
group. Urea PS values were not significantly different
between groups; however, since cardiac output tended to be
lower in mitral valve replacement patients, when 
PS is normalized to flow, the mitral valve replacement group is significantly higher.

In 19 studies in eight patients fractional water content of whole blood averaged 0.81 ± 0.02 so and fractional water content of plasma averaged 0.91 ± 0.01 so. Figure 6 shows the corrected extravascular lung water volume calculated from the formulas of Goresky et al.12 using hematocrit and blood and plasma water content measured at the time of each study for the 19 studies where all of the variables were measured plotted against extravascular lung water calculated using only albumin as the intravascular indicator and neglecting blood water content. Hematocrit in this group ranged from 0.34 to 0.50, and cardiac output ranged from 39 to 112 ml/sec. In spite of the wide range of water volumes, hematocrits, and cardiac outputs, the two values correlate extremely well.

Discussion

A practical and clinically useful method for detecting increased lung vascular permeability would be of benefit in identifying diseases where such a lesion occurs and in following the effects of therapy. Because several small hydrophilic molecules are confined to the vascular space in a
single pass across the lung circulation, a number of investigators have reasoned that when vascular permeability is increased such substances might leak from the vascular bed rapidly enough to alter their single pass indicator dilution curve, and thus provide a way of detecting increased permeability.16, 18 In a series of studies in anesthetized dogs, we showed that the mean transit time volume of urea did not exceed that of albumin, either under baseline circumstances or when lung vascular pressures were acutely elevated enough to produce severe pulmonary edema. However, when pulmonary edema was produced by increasing vascular permeability with alloxan, the distribution volume of urea exceeded that of albumin.10 Extraction and permeability-surface area products for 14C-urea calculated by the method of Crone14 also increased in alloxan edema, but did not increase in high pressure edema.

In the present studies, the relationships of 14C-urea transpulmonary indicator curves to those of intravascular indicators were different in patients undergoing mitral valve replacement than in patients undergoing aortocoronary bypass. In the aortocoronary bypass patients the 14C-urea curves fell between the curves for 125I-albumin and 51Cr-erythrocytes. However, in mitral valve replacement patients, the 14C-urea curves had a lower peak and more shallow downslope than either intravascular indicator. These differences are reflected in both mean transit time volume calculations and calculations of 14C-urea extraction.14

The relationship between urea and albumin mean transit time volumes in the group of patients having aortocoronary bypass was similar to that which we saw under baseline conditions in dogs. Urea volume tends to be slightly less than that of albumin because urea distributes in both red cells and plasma. Since red cell transit time is shorter than that of plasma,19 the effect is to shorten urea mean transit time and

![Figure 4](http://circ.ahajournals.org/)

**Figure 4** Extravascular lung water in the two study groups before and after surgery. Mean extravascular lung water was higher in the mitral valve replacement group at each study time. Lung water in the aortocoronary bypass group was significantly lower than baseline 6 hrs (P < 0.05) and 24 hrs (P < 0.05) after surgery. All except one of the mitral valve replacement patients had lower lung water six hrs postoperatively than before surgery.

![Figure 5](http://circ.ahajournals.org/)

**Figure 5** Excess urea to albumin volume ratio in the two study groups at each study time. The value consistently averaged less than 1.0 in the aortocoronary bypass group and greater than 1.0 in the mitral valve group. Differences between groups were significant before (P < 0.05) and 6 hrs after (P < 0.05) surgery. The values after surgery were not significantly different from preoperative values in either group.
thus make its mean transit time volume smaller than that of albumin if it does not leave the vascular space.

The ratio of urea volume to albumin volume was greater than 1.0 in the mitral valve replacement patients both before and after surgery, and was significantly greater than that of the aortocoronary bypass patients. This is the kind of effect we saw with increased permeability but not with acute large elevations of pulmonary vascular pressures in the dog experiments. If a substantial amount of urea leaves the vascular space during a single transit through the lung, it washes out more slowly than the intravascular indicators and thus its mean transit time is longer and its mean transit time volume is larger. In the kidney, where urea readily crosses capillary walls, it has been suggested that the distribution volume is limited by a slow urea-red cell equilibria

tion (half time of about 0.3 sec) relative to capillary transit time, so that some urea is effectively “trapped” in red cells. This problem has been investigated recently by others. Based on estimates of lung capillary transit time from morphological data in dogs (estimated capillary transit time 0.8 sec), we have argued that red cell trapping should not substantially influence urea extraction and mean transit time in dogs. Ziegler and Goresky have proven that red cell trapping of urea does not occur in the heart by demonstrating that the urea outflow curve was similar whether perfusion was with whole blood or erythrocyte free plasma. Any red cell trapping effect in our experiments would make the mean transit time volume an underestimate. The downslope extrapolation may exclude some of the urea indicator, as suggested by a recovery lower than for intravascular indicators, and this would also make the mean transit time volume lower than the actual distribution volume. It is possible that chronic elevations in pulmonary vascular pressures in humans where capillary surface area is larger than in dogs results in such a long capillary transit time that urea is able to leak out in a single pass through the circulation although permeability is not altered.

Calculations of 14C-urea extraction by an upslope difference technique showed higher urea extraction in mitral valve replacement patients than in aortocoronary bypass patients. There was no difference in urea permeability-surface area (PS) products between the groups. However, when PS was normalized to flow, the values in the mitral valve replacement group became significantly higher (table 4). These calculations suggest that the differences in the urea curves between study groups were caused by differences in cardiac output, which tended to be lower (and thus capillary transit time longer) in mitral valve replacement patients, rather than by differences in capillary permeability or sur-

<table>
<thead>
<tr>
<th>Patient no</th>
<th>Age (yrs)</th>
<th>Body Wt (kg)</th>
<th>Sex</th>
<th>NYHA class*</th>
<th>Cardiopulmonary bypass time (mins)</th>
<th>Study time</th>
<th>Hct</th>
<th>t1/2</th>
<th>t1/2</th>
<th>Recovery (relative to 14Cr)</th>
<th>IH</th>
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<tr>
<td>VH1-74</td>
<td>39</td>
<td>80</td>
<td>M</td>
<td>II</td>
<td>66</td>
<td>24 hrs</td>
<td>0.40</td>
<td>1.00</td>
<td>0.93</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>VH5-74</td>
<td>55</td>
<td>53</td>
<td>F</td>
<td>II</td>
<td>67</td>
<td>preop</td>
<td>0.38</td>
<td>1.00</td>
<td>0.90</td>
<td>1.05</td>
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<tr>
<td>VH6-74</td>
<td>56</td>
<td>54</td>
<td>M</td>
<td>II</td>
<td>65</td>
<td>6 hrs</td>
<td>0.46</td>
<td>1.00</td>
<td>0.95</td>
<td>0.94</td>
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</tr>
<tr>
<td>VH7-74</td>
<td>45</td>
<td>85</td>
<td>F</td>
<td>II</td>
<td>105</td>
<td>24 hrs</td>
<td>0.41</td>
<td>1.01</td>
<td>0.94</td>
<td>0.92</td>
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<td>48</td>
<td>F</td>
<td>II</td>
<td>82</td>
<td>preop</td>
<td>0.39</td>
<td>1.00</td>
<td>0.95</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>VH12-74</td>
<td>20</td>
<td>52</td>
<td>M</td>
<td>III</td>
<td>93</td>
<td>6 hrs</td>
<td>0.39</td>
<td>1.02</td>
<td>0.94</td>
<td>0.94</td>
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</tr>
<tr>
<td>VH13-74</td>
<td>34</td>
<td>43</td>
<td>F</td>
<td>III</td>
<td>70</td>
<td>6 hrs</td>
<td>0.39</td>
<td>1.00</td>
<td>0.95</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>VH14-74</td>
<td>36</td>
<td>60</td>
<td>M</td>
<td>II</td>
<td>150</td>
<td>24 hrs</td>
<td>0.40</td>
<td>1.00</td>
<td>0.99</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>Mean ± st.</td>
<td>42</td>
<td>59</td>
<td>M</td>
<td>II</td>
<td>87</td>
<td>preop</td>
<td>0.39</td>
<td>1.00</td>
<td>0.95</td>
<td>0.96</td>
<td></td>
</tr>
</tbody>
</table>

*See footnotes to table 2.
A longer capillary transit time could allow more urea to leak out of the vascular space. Also, if red cell trapping were occurring, a longer transit time could decrease this effect. There are questions about the accuracy of PS calculations and these have been discussed extensively by others. In addition we did not see distortions of the \(^1^4\)C-urea indicator curve like those in mitral valve replacement patients in dog experiments when pulmonary vascular pressures were markedly increased. We did see such changes when permeability was increased.

Extravascular lung water measured by indicator dilution has been found to decrease in the early postoperative period both in patients having mitral valve replacement and in those having aortic valve replacement. Parker et al. have suggested that this may be the result of patchy decreases in perfusion. We found that indicator dilution lung water decreased after surgery both in patients having aorticcoronary bypass and in those having mitral valve replacement, documenting that the change is not related to the type of cardiac operation. Comparisons of the lung water measurements at 24 hours postoperatively with the other studies in our patients are complicated by the fact that the patients were being mechanically ventilated at the time of the preoperative and six hours postoperative studies, but not at 24 hours postoperatively: mechanical positive pressure ventilation may affect the indicator dilution lung water measurement. The accuracy of indicator dilution estimates of extravascular lung water depends not only on perfusion, but also on complete recovery of the \(^1^H\)-water indicator. In most reported studies, as in our studies, recovery of \(^1^H\)-water is less than for intravascular indicators, presumably because the downslope extrapolation excludes some late returning water label. This will make the water volume estimate lower than the actual water distribution volume. The magnitude of this error depends on the time course of return for the fraction of indicator excluded by downslope extrapolation. As discussed by others, this may help explain why indicator estimates of lung water are always lower than postmortem measurements. Because of these problems, the changes in lung water measured by indicator dilution following cardiac surgery cannot be assumed to indicate true changes in lung water content unless verified by more direct methods. In fact, in all circumstances in which indicator methods are used to measure lung water, the problem of possible underestimation of actual lung water content must be carefully considered.

Gorey, Cronin, and Wangel have presented theoretical and experimental data showing that when extravascular lung water volume is calculated from indicator dilution curves, the intravascular transit time should be a composite of red cell and albumin transit times, weighted for hematocrit and the relative water content of red cells and plasma, and that instead of whole blood flow, water flow (whole blood flow \(\times\) fractional water content of blood) should be used in the calculation. Our studies in dogs showed that especially when pulmonary vascular pressures were elevated by inflating a

### Table 4. \(^1^4\)C-Urea Extraction (E), Permeability-Surface Product (PS) and PS Normalized to Cardiac Output (PS/F) for Patients Having Aorticcoronary Bypass and Mitral Valve Replacement

<table>
<thead>
<tr>
<th>(\text{E (ml/sec)})</th>
<th>(\text{PS (ml/kg)})</th>
<th>(\text{PS/F} (\text{ml/min \times} \text{ kg}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortocoronary bypass</td>
<td>0.14 - 0.01</td>
<td>11.1 - 0.9</td>
</tr>
<tr>
<td>Mitral valve</td>
<td>0.17 - 0.01*</td>
<td>10.4 - 1.0</td>
</tr>
</tbody>
</table>

*Significantly different from aorticcoronary bypass group \((P < 0.05)\).
balloon in the left atrium, there were large differences between extravascular water calculated using the corrected formulas and that using only albumin as the intravascular indicator.\textsuperscript{10} Although this problem has been recognized by investigators making measurements in humans,\textsuperscript{22,26} there has been no data available to determine the magnitude of the error resulting from the use of a single intravascular indicator. Because of the additional radioactivity and more complicated analysis, albumin alone has been used most often in human studies.\textsuperscript{9,11,20,26} We measured all of the variables in Goresky's formulas in 19 human studies, and found an excellent correlation between lung water calculated in the usual way and that calculated from the corrected formulas. The main difference in the two values is due to the correction for water flow as opposed to whole blood flow. The patients studied in this way had a broad range of water volumes, hematocrits, and cardiac outputs, and we think it reasonable to assume that the comparisons are representative of human studies in general. If desired, the equation for the relationship shown in Figure 6 can be used as a correction factor for extravascular lung water calculations made in the usual way. The additional radioactivity and difficulty involved in using two intravascular indicators is probably not justified for the measurement of extravascular lung water in humans.

We conclude from these studies that in patients undergoing aortocoronary bypass the behavior of urea in a single pass across the lung circulation is similar to that in normal dogs, that is, calculated urea distribution volume is slightly smaller than that of albumin. However, in patients undergoing mitral valve replacement, urea behaves differently. This difference is reflected in a urea mean transit time volume larger than that of albumin and in a higher urea extraction in these patients. Calculations of permeability-surface area products suggest that the differences may be due to a lower cardiac output in mitral valve replacement patients, but further studies are necessary to determine whether the differences in urea relative to intravascular indicators in mitral valve replacement patients are entirely a result of hemodynamic differences. We saw no evidence that cardiopulmonary bypass increased lung vascular permeability. Lung water measured by indicator dilution appears to decrease early in the postoperative period after cardiac surgery regardless of the type of surgery or the preoperative clinical cardiac status.

We demonstrated that the error in extravascular lung water calculations introduced by using only albumin as the intravascular indicator is constant over a wide range of cardiac outputs, hematocrits, and lung water volumes, and we presented a relationship which can be used to correct the usual calculations for this error.

References

Lung water and urea indicator dilution studies in cardiac surgery patients. Comparisons of measurements in aortocoronary bypass and mitral valve replacement.
K L Brigham, S L Faulkner, R D Fisher and H W Bender, Jr

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