Pressure and Oxygen Content Measurements Distal to Temporary and Permanent Unilateral Occlusion of a Pulmonary Artery in Dogs

By LEON CUDKOWICZ, M.D., M.R.C.P.

Both pressure and oxygen content of blood in the left pulmonary artery distal to an inflated balloon simulate that observed in the wedged cardiac catheter position. Clamping the ipsilateral pulmonary veins after inflation of the left pulmonary artery balloon, in this or in the reverse order, produces a rise in pressure distal to the balloon that exceeds the resting left pulmonary artery pressure. No corresponding increase in oxygen content of blood sampled distal to the inflated balloon, compared with that in the unoccluded pulmonary artery, could be demonstrated. This contrasts with the flow of arterialised blood that had been sampled after some months of permanent left pulmonary artery occlusion from the same position. The pressures both proximal and distal to the site of permanent occlusion are approximately the same.

ARterialized blood in unwedged cardiac catheter positions in major branches of the pulmonary artery has been demonstrated in a variety of lung diseases in man, particularly bronchiectasis suggesting its source of origin from precapillary bronchial-pulmonary anastomoses. Autopsy injection studies of fresh and normal human lungs have failed to show such precapillary anastomoses in the pulmonary arteries at levels proximal to a diameter of 100 μ; in 5 control patients with normal lungs, studied by means of differential catheterization of the lobar branches of their pulmonary arteries, arterialised blood in unwedged catheter positions could not be found.

A comparative study in dogs was therefore undertaken and was calculated to demonstrate the normal pressure and oxygen contents in the blood of the lobar branches of the pulmonary artery, and their changes, subsequent to a period of occlusion, of a main pulmonary artery branch, adequate to ensure the formation of a measurable collateral arterial flow through precapillary-bronchial to pulmonary-artery anastomoses distal to the occlusion. It is the purpose of this report to present the results of this study.

Methods

Temporary Occlusion of the Left Main Pulmonary Artery and Veins. A size 8 Dotter Lukas double-lumen balloon catheter, with one lumen opening distal to the balloon, was placed under fluoroscopy through an external jugular vein into the left pulmonary artery of intact normal dogs anaesthetised with intravenous pentobarbital (30 mg./Kg.). A second catheter, for the injection of radioactive iodinated serum albumin through a femoral vein, was advanced to the right atrium, and the adjacent femoral artery was utilized for arterial pressure records and blood samples. Routine pressure records and blood samples in these experiments were taken as follows: (1) the left pulmonary artery with the catheter tip lying free, (2) after wedging the catheter tip firmly in the left lower lobe pulmonary artery, and (3) after withdrawal of the catheter tip to position (1) and inflation of the balloon. After these preliminary measurements, which constituted procedure 1 in all experiments, the chests of the animals were opened by an incision in the fourth left intercostal space, and positive-pressure oxygen breathing commenced. In this second procedure the tip of the cardiac catheter in the left pulmonary artery was verified by palpation and the measurements of procedure 1 were repeated. Occasionally the inflated balloon in the open-chest preparation-
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tended to slip back toward the main pulmonary artery and needed to be secured proximally by a loose ligature around the left pulmonary artery just outside the pericardium. Unless the inflated balloon was so anchored, an obstruction to flow through the right main pulmonary artery produced a rise in main pulmonary artery pressure.

Following the inflation of the balloon, the pulmonary veins on the same side were clamped near their entry into the left atrium; pressures distal to the balloon were registered for a period of 15 min. and blood samples taken or attempted at 5 minute intervals. On 4 occasions the procedure was reversed: the veins were clamped before the inflation of the balloon. In 2 dogs (studied with Dr. R. Nius at the Veterans Administration Hospital, West Haven), a small polyethylene catheter was inserted into 1 left pulmonary vein and threaded a short distance toward the lung before clamping this vein near the atrial end. In the case of one of these animals, simultaneous pressures in that vein were recorded with those in the left pulmonary artery during procedure 2.

At the end of this procedure the left pulmonary artery was firmly occluded with a polyethylene snare which was left in situ. A needle guide was sewn on the left atrium and the chest was closed. All animals were studied thereafter at intervals of 3 months for determining the development of a systemic left lung collateral flow.

Permanent Left Pulmonary Artery Occlusion. As soon as studies, with the method designed by Bloomer et al., as well as with periodic isotope dilution, suggested an appreciable collateral systemic flow to the left lung, the left chest was reopened through a fifth intercostal-space incision.

The actual site of occlusion, by the snare on the left pulmonary artery, seldom exceeded 3 mm. in width, but surgical restoration of a continuous lumen was impracticable because of extensive vascularization of the adjacent adhesions. Once the pulmonary artery was carefully freed from the surrounding adhesions, a needle or a fine polyethylene catheter was introduced into the distal lumen beyond the snare. Pressures were registered simultaneously, proximally and distal to the snare, and corresponding samples were collected. Pulmonary venous occlusion became impossible during this procedure because of adhesions between the hilar surface of the left lung, pericardium and left atrium. The animals were subsequently killed; in every instance there were patent lumina on both sides of the snare.

Pressures were recorded on a Hathaway or Sanborn multiple-channel recorder, and with the former they were also monitored on an oscilloscope. Zero levels were referred to the top of the table. The oxygen content of whole blood was determined by the Van Slyke-Neill apparatus and oxygen content and capacity were determined with the Roughton-Scholander syringe method. All analyses were carried out in duplicate. After flushing of the catheter with 5 ml. of blood, the samples were usually withdrawn over a period of 1 min. into heparinized syringes. The volume of flush varied with the site of sampling. In the pulmonary wedge position or after inflation of the balloon a small flush yield precluded sampling for analysis.

RESULTS

Pressure Patterns. In 11 intact dogs, the drop in pulmonary artery pressure distal to the inflated balloon corresponded in magnitude to the pressure gradient between the left pulmonary artery and left lower pulmonary lobar capillaries, when these were separately determined by wedging the catheter tip. The contour of the pressure tracing distal to the inflated balloon assumed a pulmonary capillary configuration in every instance (fig. 1).

In 9 dogs, breathing oxygen and with the chest open, inflation of the balloon produced the same pressure drop in the left pulmonary artery as in the intact animals, with values and contours simulating those from the wedged position. The application of clamps to the pulmonary veins near the left hilum, after inflation of the balloon in the left pulmonary artery, was accompanied by a gradual rise in pressure, as measured distal to the inflated balloon. This rise reached its maxi-

![Fig. 1. Comparison of pulmonary wedge pressure contour with that distal to inflated balloon (dog no. 597). Time lines = 0.1 sec.](image-url)
maximum after 1 to 15 min., but occasionally also after a few seconds. The emerging pressure curve resembled that of the resting pulmonary artery pressure, but both systolic and diastolic values were, in 4 instances, twice as high as those recorded before occlusion (fig. 2). It is unlikely that the pressure curve resulted from a leak in the balloon during the clamping of the left pulmonary veins, since the ligature proximal to the inflated balloon almost occluded the pulmonary artery lumen. The same pressure patterns obtained upon reversal of the procedure. Clamping of the left pulmonary veins alone had no appreciable effect on left pulmonary artery pressure, but upon subsequent inflation of the balloon this pressure dropped to pulmonary capillary levels and stayed there for about 1 min. It then rapidly rose and exceeded both the diastolic and systolic resting levels in the left pulmonary artery (fig. 2). In 1 animal, left pulmonary venous pressure was simultaneously recorded through a small polyethylene catheter inserted proximal to the clamp. During inflation of the balloon alone the pulmonary venous pressure fell. It rose above its resting value with the application of the pulmonary venous clamps. This rise was almost instantaneous and maintained that level during the time of observation. Wave contours in the pulmonary venous pressure tracing ceased with the inflation of the balloon. The pulmonary artery pressure proximal to the permanent snare occlusion were within the normal range for these animals. The distal pressures were slightly lower, particularly in dog no. 590. The distal pressure contours again resembled those of the proximal pulmonary ar-
tery segment, and compared with those noted during temporary occlusion of the left pulmonary artery and veins (fig. 3).

**Oxygen Content.** In 9 successful experiments the oxygen content of blood sampled from the left main pulmonary artery was significantly lower than that of blood aspirated either from the wedge position or distal to the inflated balloon. Pulmonary wedge samples of adequate yield were obtained with some difficulty in only 6 out of 11 experiments, and in 9 out of 11 instances from the pulmonary artery segment distal to the inflated balloon. Pulmonary wedge position samples and those collected distal to the balloon had similar oxygen contents in 5 out of 6 observations.

Aspiration of blood samples, from wedge positions and after balloon occlusion, was equally difficult in dogs with their chests opened. The oxygen content of blood samples taken after balloon inflation again exceeded that of samples obtained before inflation, and in 2 instances, when comparisons also could be made with samples aspirated from wedge positions, the latter showed a somewhat higher content.

Following the temporary occlusion of both the left pulmonary artery and veins, sampling distal to the balloon was at first fairly easy. However, after a yield of about 8 to 10 ml., the flow ceased, irrespective of height of pressure, and further samples could not be obtained during the remaining 10 min. of the experiment, either by catheter or by direct needle puncture. The oxygen content of these samples is of interest, inasmuch as it was lower than that of samples aspirated following balloon occlusion alone; in 4 experiments it was slightly less than that of the mixed venous blood taken from the left unoccluded pulmonary artery. The inflation of the balloon was invariably accompanied by a pallor of the left lung which changed to a deep red on clamping the pulmonary veins on the same side.

Blood sampling, from the distal lumen of the permanently occluded pulmonary artery, by needle puncture or with a fine polyethylene catheter, yielded a free flow of arterial blood. The oxygen content of these samples exceeded that of samples taken from the proximal lumen, and resembled that of samples from the femoral artery. Bronchorespirometry before the chest was opened showed little oxygen uptake by the left lung when both lungs were on oxygen. With the normal lung on ambient air, however, oxygen uptake by the left lung increased, indicating perfusion of the alveolar capillaries of the left lung by a collateral systemic blood flow.

**DISCUSSION**

In this study, the oxygen content of blood samples from unwedged catheter positions in the left pulmonary artery of normal animals was lower than that of samples obtained either distal to balloon occlusion or from wedge positions. All samples from the left pulmonary artery with a lower oxygen content were aspirated in the presence of a typical pulmonary artery pressure curve. This is in contrast to the pulmonary-capillary type of contour that obtained whenever samples with a higher oxygen content were collected. At no time, apart from the special circumstances attending permanent pulmonary artery occlusion, did the blood yield a high oxygen content when harvested in the presence of a normal pulmonary artery tracing.

The absence of a contour other than that of pulmonary artery pressure recorded distal to the permanent snare occlusion of the left pulmonary artery is of interest and cannot be satisfactorily explained. It is also of some interest that a comparable contour emerged after temporary occlusion of both pulmonary artery and veins. Similarly the contours of the pulmonary artery pressure curve in the lobar branches of patients who yielded arterialized blood from these sites were of the same type.3

Temporary occlusion of both the pulmonary artery and veins on the left side led to the rise in pressure noted by Shedd et al.,7 and persisted throughout the 15 minute period of occlusion. The same rise in pressure attended the reversal of the procedure by clamping the veins before occluding the pulmonary ar-
TABLE 1.— Oxygen Content and Capacity in Volumes Per Cent

<table>
<thead>
<tr>
<th>Dog no.</th>
<th>Before occlusion of left pulmonary artery</th>
<th>During occlusion of left pulmonary artery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LPA</td>
<td>L.I.L. pulm. cap.</td>
</tr>
<tr>
<td></td>
<td>Content</td>
<td>Capacity</td>
</tr>
<tr>
<td>577</td>
<td>10.65</td>
<td>15.58</td>
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<tr>
<td>583</td>
<td>8.71</td>
<td>14.06</td>
</tr>
<tr>
<td>584</td>
<td>12.3</td>
<td>18.96</td>
</tr>
<tr>
<td>584</td>
<td>13.8</td>
<td>18.65</td>
</tr>
<tr>
<td>590</td>
<td>10.43</td>
<td>15.32</td>
</tr>
<tr>
<td>596</td>
<td>9.9</td>
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<td>597</td>
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</tr>
<tr>
<td>600</td>
<td>15.5</td>
<td>18.69</td>
</tr>
<tr>
<td>AYA</td>
<td>11.3</td>
<td>18.82</td>
</tr>
</tbody>
</table>

L.I.L. pulm. cap., left lower lobe pulmonary capillary.
LPA, left pulmonary artery.
FA, femoral artery.
Samples listed as oxygen content alone were analysed in the Van Slyke apparatus.

<table>
<thead>
<tr>
<th>Dog no.</th>
<th>Before LPA occlusion</th>
<th>LPA occlusion alone</th>
<th>LPA and Left pulm. venous occlusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LPA</td>
<td>L.I.L. pulm. cap.</td>
<td>LPA</td>
</tr>
<tr>
<td></td>
<td>Content</td>
<td>Capacity</td>
<td>Content</td>
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<tr>
<td>573</td>
<td>15.45</td>
<td>19.09</td>
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</tr>
<tr>
<td>587</td>
<td>12.8</td>
<td>---</td>
<td>No sample</td>
</tr>
<tr>
<td>590</td>
<td>14.0</td>
<td>18.55</td>
<td>No sample</td>
</tr>
<tr>
<td>594</td>
<td>15.63</td>
<td>21.9</td>
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</tr>
<tr>
<td>597</td>
<td>15.89</td>
<td>17.75</td>
<td>16.89</td>
</tr>
</tbody>
</table>

Oxygen contents in proximal and distal portions of permanently occluded left pulmonary artery.

<table>
<thead>
<tr>
<th>Dog no.</th>
<th>Proximal left pulmonary artery</th>
<th>Distal left pulmonary artery</th>
<th>Femoral artery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Content</td>
<td>Capacity</td>
<td>Content</td>
</tr>
<tr>
<td>573</td>
<td>13.96</td>
<td>17.05</td>
<td>17.44</td>
</tr>
<tr>
<td>590</td>
<td>14.33</td>
<td>16.84</td>
<td>15.95</td>
</tr>
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</table>

tery. The changes in pulmonary venous pressure proximal to the clamps were less dramatic and amounted to about 2 mm. Hg above the resting level. The yield of blood from the isolated vascular segment 5 min. after temporary occlusion, as well as in the remaining 10 min. of observation, was small. In 4 instances the oxygen content of this blood was less than that of the unoccluded pulmonary artery, possibly because of stagnation.

The pressure distal to the unilateral permanent occlusion was normal, even in the presence of an appreciable systemic arterial flow perfusing the left lung. A satisfactory explanation for the rise in pressure which followed the unilateral temporary occlusion...
of pulmonary artery and veins cannot be advanced without conjecture. If this rise in pressure is to be interpreted as a systemic arterial pressure following the inflow of arterial blood through pre-existing precapillary bronchopulmonary anastomoses, arterialised blood should have been aspirated distal to the occluded balloon in the same way as it was distal to the permanently occluded pulmonary artery. In view of the absence of such arterialised blood over a period of 15 min. of raised pressure it is unlikely that precapillary anastomoses between the bronchial and pulmonary arteries are a normal component of the distal pulmonary artery bed. These anastomoses can be demonstrated at autopsy and by cardiac catheterization in association with certain lung diseases in segmental pulmonary artery branches having diameters in excess of 100μ, but not in the normal human pulmonary artery tree. The formation of precapillary bronchopulmonary anastomoses with a sizeable collateral flow follows permanent or very prolonged pulmonary artery occlusion. It is gradual in evolution and, when fully developed, demonstrable by arterial blood distal to the snare occlusion.

**Summary**

Oxygen content and the pressures in the left pulmonary artery of 11 intact dogs were determined before and after inflation of a balloon near the tip of a cardiac catheter. The pressure distal to the inflated balloon dropped to pulmonary "capillary" level and assumed a corresponding contour. Similarly, the oxygen content of blood, aspirated distal to the inflated balloon, resembled that from pulmonary wedge samples. Simultaneous temporary occlusion of the left pulmonary artery and veins in open-chest experiments led to a rise in pressure in this isolated vascular segment which followed the initial drop in pressure after balloon inflation. This rise in pressure was also reflected in a much smaller rise in pulmonary venous pressure. All blood samples that were recovered from this isolated pulmonary artery segment towards the end of the first five-minute phase of raised pressure showed oxygen contents which were either the same or somewhat lower than that in the unoccluded pulmonary artery.

In dogs with permanent snare occlusion of the left pulmonary artery arterial blood was sampled from the patent lumen distal to the obstruction. The pressure in this vascular segment approximated that of the main pulmonary artery and showed a similar contour.

**Acknowledgments**

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**SUMMARIO IN INTERLINGUA**

Le contento de oxygeno e le pression in le arteria pulmonar sinistre de 11 canes intacte esseva determinate ante e post le inflation de un balloon presso al puncta de un catheter cardiac. Le pression in sitos distal al inflate ballon descendeva al nivello "pulmono-capillar" e disveloppava un contorno corrispondente. Similemente, le contento de oxygeno in sanguine aspirate ab sitos distal al sito del inflate ballon resimilava illo trovate in specimen a cuneo pulmonar. Le simultanea occlusion temporari del arteria e del venas sinistro-pulmonar (in experimentos a thorace aperte) resultava in un augmento del pression in iste isolate segmento vascular post le reduction initial del pression effectuate per le inflation del balloon. Iste augmento del pression esseva etiam reflectite in un augmento—multo minus marcate—del pression pulmo-venose. Omne le specimen de sanguine prendite ab iste isolate segmento de arteria pulmonar versus le fin del prime cinque minutas de pression elevate monstrava valores pro le contento de oxygeno que esseva identic o levemente inferior al valores observate in non-occludite arterias pulmonar.

In canes con occlusion permanente del ar-
teria sinistro-pulmonar (effectuate per medio de ansas de filo), specimens de sanguine arterial esseva obtenite ab le passage patente in sitos distal al sito del obstruction. Le presision in iste segmento vascular se approximava a illo del major arteria pulmonar e exhibiva un simile contorno.

REFERENCES
Pressure and Oxygen Content Measurements Distal to Temporary and Permanent Unilateral Occlusion of a Pulmonary Artery in Dogs
LEON CEDKOWICH

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