THE COLLAPSE FACTOR IN THE MEASUREMENT OF VENOUS PRESSURE

The Flow of Fluid through Collapsible Tubes

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If veins were rigid tubes, then a change in mean right auricular pressure would cause a corresponding change in the peripheral venous pressure, provided the velocity of blood flowing along the veins remained constant. However, veins are not rigid, but collapsible, and it has been shown by Lyon, Kennedy and Burwell (1938), and by Holt (1940), that peripheral venous pressure, referred to the level of the heart as zero, is increased when the vein is above heart level because the veins collapse. Carrier and Rehburg (1923) have also shown that the collapse of peripheral veins and capillaries may maintain capillary pressure at a high level when the capillary is above heart level.

Since veins are collapsible tubes, and the pressure in the right auricle is generally agreed to be subatmospheric, and there is a small positive tissue space pressure around the veins tending to collapse them, it was thought that changes in mean right auricular pressure might not affect peripheral venous pressure because the veins just before entering the chest might be partially collapsed.

METHODS AND RESULTS. When the veins entering the upper end of the thoracic cage were dissected out in the living dog, they were seen to be normally partially collapsed or to dilate and collapse synchronously with respiration. When the animal breathed air which was under a negative pressure the veins were seen to collapse more completely, and when air under a positive pressure was breathed the veins became dilated. The inferior vena cava was seen to collapse, after dissecting the liver away from it, when air under a negative pressure was breathed, but was not seen to collapse with normal respiration.

In ten barbitalized dogs with the chest closed, and placed in the supine position, mean peripheral venous pressure was measured in the femoral,
CEPHALIC, OR JUGULAR VEIN BY A MODIFICATION OF THE METHOD OF MORITZ AND TABORA (1910). AT THE SAME TIME MEAN RIGHT AURICULAR PRESSURE WAS MEASURED BY MEANS OF A SALINE MANOMETER CONNECTED TO A CANNELLA THAT PASSED INTO THE RIGHT AURICLE BY WAY OF THE EXTERNAL JUGULAR VEIN. THE VENOUS PRESSURES WERE REFERRED TO THE LEVEL OF THE CANNELLA TIP IN THE RIGHT AURICLE AS ZERO. IN SOME CASES PERIPHERAL VENOUS AND AURICULAR PRESSURE FLUCTUATED SEVERAL MILLIMETERS WITH EACH RESPIRATION; IN THESE CASES THE PRESSURES WERE READ AT THE PEAK OF INSPIRATION AND AT THE PEAK OF EXPIRATION (FIG. 1). THE TRACHEA WAS CANNELLATED AND CONNECTED TO A BREATHING CHAM-

\[ \text{Venous and Auricular Pressure (cm. Saline)} \]

\[ \text{Femoral Venous Pressure} \]

\[ \text{Auricular Pressure} \]

\[ \text{Level of Needle in Vein} \]

\[ \text{Chamber Pressure (cm. H}_2\text{O)} \]

**Fig. 1.** The effect of changing the breathing chamber pressure on right auricular and femoral venous pressure. +, above atmospheric pressure. --, below atmospheric pressure.

The spirometer was ventilated with fresh air at a rate of fifteen liters per minute. The dog breathed from the chamber continuously, and when the pressure in the chamber was changed to any positive or negative value five minutes or longer were allowed before the venous and auricular pressure readings were taken. When the chamber pressure was increased the intra-thoracic pressure was increased and auricular pressure rose; when the chamber pressure was decreased the intra-thoracic and auricular pressures decreased.
The results of a typical experiment measuring auricular pressure and femoral venous pressure are shown in figure 1. When the breathing chamber pressure was increased the auricular pressure and peripheral venous pressure increased. When the chamber pressure was decreased the auricular pressure decreased but the peripheral venous pressure did not change.

Similar results were obtained on the jugular and cephalic veins with the exception that when the cephalic vein was used a rise in auricular pressure of a few centimeters of saline caused no increase in cephalic venous pressure, but a further rise in auricular pressure caused an increase in cephalic pressure. With the dog in the standing position results similar to those obtained on the femoral vein were obtained on the femoral and cephalic veins with the exception that a slight decrease in auricular pressure generally caused a decrease in peripheral venous pressure, but on further lowering auricular pressure the peripheral venous pressure remained constant. In all of the experiments described the vein was held below heart level. If the vein was held above heart level auricular pressure had to be increased several centimeters of saline before there was any rise in the peripheral venous pressure.

The maintenance of a high peripheral venous pressure when the auricular pressure was low might be explained by an increased rate of flow along the veins resulting from an increased cardiac output when the intra-thoracic pressure was low. In order to rule out this possibility a portion of the venous system of a dead dog was perfused with saline. The brachial, axillary, subclavian and innominate veins on one side, and the superior vena cava were dissected out, left in place, and all side branches entering these veins were tied. This left one large vein, with no open side branches, extending from the antecubital space to the right auricle. The brachial vein was cannulated in the antecubital space and the superior vena cava cannulated at the level of the right auricle. This system was perfused with saline, under a constant head of pressure, through the peripheral end of the brachial vein. The pressure in the peripheral brachial vein and in the superior vena cava was measured. With subatmospheric pressures in the superior vena cava the results were comparable to those obtained in the experiments on the femoral vein in the living dog. A similar experiment was performed on the inferior vena cava with like results. Thus it was shown that it was not necessary for the rate of flow along the veins to increase in order to maintain a constant peripheral venous pressure when the auricular pressure was greatly decreased.

In order to study how the collapse of veins might affect peripheral venous pressure a model (fig. 2) was set up using thin walled rubber tubes to represent veins or using the excised jugular vein of the dog. Water flowed from the Mariot bottle reservoir along heavy walled rubber tubing to a section of collapsible tubing and out through more heavy walled rubber tubing.
The pressures, $P_1$, above the collapsible segment, and $P_2$, below the collapsible segment were measured simultaneously with the rate of outflow. The collapsible segment was surrounded by a glass jacket in which the pressure was varied at will. The factors controlling the rate of flow of water through the collapsible tubes were studied by changing one of the above pressures, keeping the other two pressures constant, and measuring the rate of outflow into a graduate cylinder. In this system, when the outlet tube was lowered to a certain point, the pressure at $P_2$ became subatmospheric; thus $P_2$ corresponded to the auricular pressure, and $P_1$ to the peripheral venous pressure in the dog, while the jacket pressure corresponded to the tissue space pressure.

The effect on $P_1$ of changing $P_2$ is shown in table 1 A. When $P_2$ was above jacket pressure (atmospheric in this case) and the tube was dilated, lowering $P_2$ caused a decrease in $P_1$, and this continued until $P_2$ became slightly subatmospheric at which point the tube collapsed. Further decrease of $P_2$ caused no change or a slight increase in $P_1$.

The effect of changing $P_2$ on the rate of outflow is shown in table 1 A. When $P_2$ was above atmospheric pressure and the collapsible tube was open, lowering $P_2$ caused an increase in the rate of outflow until $P_2$ became slightly subatmospheric at which point the collapsible tube started to collapse. As the tube started to collapse it began to pulsate and as $P_2$ was further lowered the rate of pulsation became more rapid. Finally when $P_2$ was lowered still further the pulsation apparently stopped and the tube remained partially collapsed. Lowering of $P_2$, once the tube had begun to

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Fig. 2. Model used for studying the flow of water through collapsible tubes

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pulsate or to collapse, caused no change in the rate of outflow or a slight decrease.

The effect of changing $P_1$ on the rate of outflow with the tube open and again with the same tube partially collapsed, is shown in table 1 B. As $P_1$ increased the rate of flow increased in the open tube and in the partially collapsed tube. In both cases the increase in rate of flow was shown to be a linear function of the increase in $P_1$ when the data were plotted on graph paper.

### TABLE 1

*Flow of water through partially collapsed and open tubes*

<table>
<thead>
<tr>
<th>Tube</th>
<th>Open tube</th>
<th>Partially collapsed tube</th>
<th>Flow Rate</th>
<th>Rate of Outflow</th>
<th>Jacket Pressure</th>
<th>Rate of Outflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1 - P_2$</td>
<td>cm.</td>
<td>cm./min.</td>
<td>cm.</td>
<td>cm./min.</td>
<td>cm.</td>
<td>cm./min.</td>
</tr>
<tr>
<td>23.7</td>
<td>23.4</td>
<td>0.3</td>
<td>31.8</td>
<td>7.3</td>
<td>74</td>
<td>0.12</td>
</tr>
<tr>
<td>14.3</td>
<td>13.9</td>
<td>0.4</td>
<td>36.0</td>
<td>8.0</td>
<td>182</td>
<td>0.0088</td>
</tr>
<tr>
<td>0.7</td>
<td>0.2</td>
<td>0.5</td>
<td>45.0</td>
<td>8.85</td>
<td>276</td>
<td>0.0059</td>
</tr>
<tr>
<td>0.0</td>
<td>-2.4</td>
<td>2.4</td>
<td>45.5</td>
<td>9.50</td>
<td>372</td>
<td>0.0033</td>
</tr>
<tr>
<td>0.3</td>
<td>-12.1</td>
<td>12.4</td>
<td>45.5</td>
<td>10.80</td>
<td>480</td>
<td>0.009</td>
</tr>
<tr>
<td>1.0</td>
<td>-45.4</td>
<td>46.4</td>
<td>44.4</td>
<td>16.80</td>
<td>480</td>
<td>0.009</td>
</tr>
<tr>
<td>1.6</td>
<td>107.0</td>
<td>44.0</td>
<td></td>
<td>24.0</td>
<td>360</td>
<td>0.14</td>
</tr>
</tbody>
</table>

A. Effect of changing $P_1$ on the rate of flow through the jugular vein of changing $P_2$. B. Effect of changing $P_1$ on the rate of flow through a thin wall collapsible rubber tube 7 mm. in diameter (in the open tube $P_2 = 6.4$ cm. of water, jacket pressure = atmospheric; in the partially collapsed tube $P_2 = -28.5$ cm. of water, jacket pressure = 19.9 cm. of water). C. Effect of changing the jacket pressure on the rate of flow through the partially collapsed rubber tube ($P_1 = 21.3$ cm. of water, $P_2 = -28.5$ cm. of water). J.P., jacket pressure. $R$, resistance. —, minus.

* It took approximately 1 cm. water pressure to overcome the elasticity of the rubber tube and to collapse it, thus the jacket pressure is slightly higher than $P_1$ here.

The effect of changing the jacket pressure on the rate of flow when $P_1$ and $P_2$ were kept constant is shown in table 1 C. As the jacket pressure decreased the flow increased.

The fact that the rate of flow did not increase when $P_2$ was decreased, once the tube was partially collapsed (table 1 A), means that the resistance to flow through the partially collapsed tube increased as $P_2$ decreased. The resistance to flow may be calculated from the data in table 1 using the conventional formulation, $R = \frac{P_1 - P_2}{Flow}$. With the viscosity constant, as is the case in these experiments, the increase in $R$ as the tube collapses must be caused by a decrease in the cross-sectional area of the collapsed segment, to an increase in turbulence, to an increase in the length of the
partially collapsed segment, or to a combination of these factors. No increase in the length of the partially collapsed segment was detected.

Table 1A shows that in the partially collapsed tube the resistance increased as $P_2$ decreased, and table 1B that the resistance decreased as the flow increased and as $P_1$ increased, and table 1C that the resistance decreased as the jacket pressure decreased.

The length of the collapsible tube had little effect on the flow, since similar results were obtained on a collapsible tube 80 cm. long and on another 2 cm. long. When the longer tube collapsed the collapsed segment was always at the downstream 1 or 2 cm. of the tube, the rest of the tube remained open unless the flow through the system was very small. It appears that it was only necessary for the collapsible tube to be long enough and relaxed enough to collapse to give the effects of collapsible tubes described above.

The pressure:flow graphs that were plotted from the data in table 1B were straight lines, whereas in experiments on smaller tubes, such as the jugular vein, the pressure:flow graphs were smooth curves convex toward the flow axis. This apparently is the result of the abrupt change in cross-section, which occurs at the point where the cannula tips are tied into the vein, causing the flow to be turbulent (Dodge and Thompson, 1937). However, qualitative results similar to those described in table 1 were obtained on these tubes.

Discussion. The fact that peripheral venous pressure remained constant when auricular pressure was decreased greatly and in some cases when auricular pressure was increased a small amount may have been caused in part by the change in auricular pressure being associated with a change in cardiac output and with a change in the rate of flow of blood along the veins. However, since the veins were seen to collapse, and since similar results were obtained on the excised jugular vein in a model, and on the dead dog's venous system acting as a model, it would appear that the collapse of the veins near the heart was an important factor in maintaining the peripheral venous pressure normal when auricular pressure changed.

Since auricular pressure may change independently of a change in peripheral venous pressure, it appears that the usual clinical measurement of venous pressure may give little indication of the pressure in the right auricle.

In the collapsible tubes studied here, the resistance to the flow of water decreased as the head of pressure, $P_1$, increased and as the jacket pressure decreased. Lowering the pressure on the downstream side of the collapsible tube increased the resistance to flow. Thus collapsible tubes differ from rigid tubes in that the resistance to flow remains constant in rigid tubes as the pressure-drop across the tube changes (so long as the flow is not
turbulent), while in collapsible tubes the resistance changes as the pressure-drop across the tube changes. Although the increased resistance to flow offered by the partially collapsed tube might be caused in part by an increase in turbulence at the partially collapsed segment, it seems certain that part of the increased resistance is caused by a decrease in cross-section of the segment, since the cross-section is observed to decrease in size when the tube collapses and appears to decrease still further the more the tube becomes collapsed.

It should be noted that in the graphs plotted from the data in table 1 B the pressure:flow line was steeper in the collapsed tube than in the open tube, that is, it took a greater increase of $P_1$ in the partially collapsed tube than in the open tube to cause a given increase in flow. The pressure:flow lines became steeper as the collapsible tube became more collapsed, i.e., at higher jacket pressures. This was the case in both the jugular vein and the thin walled rubber tubes. The reason for the greater slope of the pressure:flow line when the jacket pressure is higher is not clear.

Since the collapsible tubes studied show pulsation in the early part of the collapsing process, there is the possibility that some part of the venous pulse seen in the veins entering the chest may be caused by this type of pulsation. Also, since the veins entering the chest do collapse when there are moderate negative pressures in the right auricle, and since it has been shown that decreasing the pressure on the downstream side of a partially collapsed tube does not increase the rate of flow through the tube, it seems that this collapse of the veins entering the chest may be a mechanism which insures a normal flow of blood into the heart but prevents over-filling of the heart and intra-thoracic vessels when large negative pressures are present in the chest as in Müller’s experiment or when a deep inspiration is taken.

SUMMARY

Right auricular and peripheral venous pressures were measured in dogs breathing from a chamber in which the pressure varied between 20 cm. of water above atmospheric and 20 cm. below. It was shown that when auricular pressure was decreased greatly and in some cases when auricular pressure was increased slightly the peripheral venous pressure remained constant. In most cases when auricular pressure increased the peripheral venous pressure was increased.

The flow of water through collapsible tubes such as the jugular vein of the dog was studied in a model. When fluid is flowing through a partially collapsed tube, increasing the pressure on the upstream side of the partially collapsed segment decreases the resistance to flow through the collapsible segment and increases the rate of flow, whereas lowering the pressure on the downstream side of the collapsible segment increases the resistance to flow through the collapsible segment and either does not change the rate of
flow or decreases it slightly. An increase in the jacket pressure around the collapsible tube increases the resistance to flow through the collapsible segment and decreases the rate of flow.

As a collapsible tube, having fluid flowing through it, starts to collapse it pulsates and as it becomes more collapsed the pulsation increases in rate on further collapse the pulsation apparently disappears.

The length of the collapsible tube is not important in controlling the length of the partially collapsed segment. It appears to be only necessary that the tube be long enough and relaxed enough to collapse in order to give the results described, and any length of collapsible tube greater than this length merely acts as a dilated or rigid tube.

REFERENCES

HOLT, J. P. This Journal 130: 635, 1940.