In a recent study, measurements of lengths, diameters, and numbers of vessels contained in a peripheral vascular bed from distributing artery to arterial capillaries were made in the living animal. From the data, total cross-sectional areas of the various portions of the arterial tree were calculated and compared with values from similar measurements of vessels in fixed tissue. In the living animal, a linear increment in total cross-sectional area was found from artery to arterial capillary, differing markedly from the long accepted concept of small increases in total area from artery to arteriole followed by a tremendous increase at the level of the capillaries. It was suggested at that time that the wide variance in results of the two studies was due mainly to inaccurate estimates in fixed tissue of the numbers of the various types of vessels, especially the capillaries. Further consideration reveals that vessel diameters may be a more important factor in accounting for the variance.

In this paper, lengths, diameters, and numbers of the collecting vessels are presented, thus completing measurements of a total vascular bed from a major distributing artery to its accompanying vein in the living animal. Comparisons are made with similar measurements and computations from fixed tissue.

Methods

The site used for measurements of the collecting vessels was the wing of the common brown bat (Myotis). The vessels in this subcutaneous area were observed in the intact, unanesthetized animal. An eyepiece micrometer was used to measure the length and inside diameter of the vessels at magnifications of 400 X and 1200 X depending on the size of the vessel being measured.

In general, the beginning and end of a venous vessel were determined in the same manner as had been used for measuring the arterial vessels in the same category. For example, the major artery was said to end at its first bifurcation while the major vein was considered to begin at the point where two large veins form a junction. An arterial bifurcation or a venous junction were easily differentiated from the branches or tributaries of these vessels.

Small veins are defined here as vessels which empty into the major vein. Their origin was found to be in general parallel to an arterial arcade, except that in the case of venous vessels the two paths of blood flow diverge rather than converge.

Venules are defined as the vessels which empty into small veins. Venules receive blood from smaller vessels, called here post-capillary venules, which in turn originate from the capillary network. In the report on arterial vessels from this laboratory, a capillary was defined as a distributing vessel which arose as a side branch of an arterial and it ended at the point where an inflowing tributary joined it, the newly formed vessel now becoming a post-capillary venule.

Results

Table 1 shows that the average length of a major vein was essentially the same as its accompanying artery while the diameter of the vein was greater than that of the artery by one-half. The major vein had twice as many inflowing tributaries as the major artery had branches. The cross-sectional area of each of the vessels was calculated and the average of these values revealed that the cross-sectional area of the major vein was more than twice that of the artery.

The average length of a small vein was the same as the average length of the small artery that ran adjacent to it, but the diameter of the small vein was twice the diameter of the small artery. Small veins had one-half again as many vessels flowing into them as small arteries had distributing branches, and the...
TABLE 1
Dimensions of Blood Vessels in the Bat’s Wing

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Average length (mm)</th>
<th>Average diameter (μm)</th>
<th>Average number of branches</th>
<th>Number of vessels</th>
<th>Total cross-sectional area (μm²)</th>
<th>Capacity (X 10⁻³)</th>
<th>Per cent capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artery</td>
<td>17.0</td>
<td>50.6</td>
<td>12.3</td>
<td>1</td>
<td>2,263*</td>
<td>38.4</td>
<td>10.1</td>
</tr>
<tr>
<td>Arteriole</td>
<td>3.5</td>
<td>19.0</td>
<td>3.7</td>
<td>12.3</td>
<td>4,144</td>
<td>54.4</td>
<td>3.8</td>
</tr>
<tr>
<td>Capillary</td>
<td>0.95</td>
<td>7.0</td>
<td>4.6</td>
<td>119.3</td>
<td>5,101</td>
<td>4.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Post-capillary</td>
<td>0.25</td>
<td>3.7</td>
<td>3.1</td>
<td>568.7</td>
<td>6,548</td>
<td>1.5</td>
<td>0.58</td>
</tr>
<tr>
<td>Vessel</td>
<td>0.02</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artery</td>
<td>1.0</td>
<td>21.0</td>
<td>5.0</td>
<td>543.4</td>
<td>78,029</td>
<td>16.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Small vein</td>
<td>3.4</td>
<td>37.0</td>
<td>14.1</td>
<td>284.5</td>
<td>27,800</td>
<td>94.7</td>
<td>25.0</td>
</tr>
<tr>
<td>Vein</td>
<td>16.6</td>
<td>76.3</td>
<td>14.3</td>
<td>1</td>
<td>4,882</td>
<td>81.0</td>
<td>21.4</td>
</tr>
</tbody>
</table>

*Average of individual cross-sectional areas.
†Calculated.

The total cross-sectional area (average of areas of individual vessels times number of vessels) of the small veins was almost seven times as large as the total cross-sectional area of the small arteries.

Arterioles and venules had the same length, but the average diameter of the venules was three times greater than the average diameter of the arterioles. There were about the same number of post-capillary venules emptying into the venules as there were capillaries leaving the arterioles. The total cross-sectional area formed by the venules was the largest in the entire vascular bed, exceeding by 25 times the total cross-sectional area formed by the arterioles.

Post-capillary venules were about the same length as the capillaries although they had a diameter twice as large. Post-capillary venules were three times more numerous than arterial capillaries. By calculation, each arterial capillary must give rise to three post-capillary venules on the average. Although there were equal numbers of post-capillary venules emptying into venules and arterial capillaries originating from arterioles, there were almost twice as many venules to receive these small vessels as there were arterioles to supply the capillaries. A diagrammatic representation of the vascular bed in figure 1 shows a possible arrangement to account for the large numbers of venules. The results of the measurements are summarized in table 1.

Figure 2 indicates that the total cross-sectional areas produced by division of arterial vessels and confluence of venous vessels show a linear increment from artery to capillary, a marked rise at the post-capillary venules, and a still further increase at the level of the venules. At the small veins, the area decreases sharply and this is followed by a small decrease to the major vein. A comparison of these values obtained from measurements in the living animal with those computed by Green using Mall’s data on fixed material is reasonably similar with the exception of the total cross-sectional area of the capillaries. Green states that his data are very rough since many assumptions are necessary. One assumption frequently made relates to the diameter of a capillary vessel which is estimated to be about eight microns, based on the diameter of the mammalian red blood cell. The two curves presented in figure 2 for total cross-sectional area can be made to agree more closely if one accepts the view that the diameter of a capillary is approximately four microns as measured in the living animal, rather than the estimated value of eight microns (see dashed line in figure 2). In defense of accepting such a diameter for the capillary, a survey of the literature reveals that in instances where the diameter was actually measured rather than estimated, the majority of the values fall well below eight microns as shown in table 2. More specifically, according to a recent compilation in which 36 capillary diameters from different mammals are given, only four are based on actual measurements and these four values are 3, 3.8, 4.6, and 5 microns. The remaining normal values, in gen-
Diagrammatic representation of relationships between arterial and venous vessels in a terminal vascular bed.

Calculations of the capacity of each of the various portions of the vascular bed and the percentage of the total volume of blood each portion contains, shows that the venous vessels can contain 80% of the total blood in the peripheral vascular bed (fig. 3).

Discussion

The importance of having measurements of the lengths, diameters, and numbers of vessels formed by the ramifications of a distributing artery and the convergence of the collecting venous system lies in their defining the proper relationships between the various portions of the vascular bed. Actual values for lengths, diameters, and numbers of vessels have no real significance except perhaps at the capillary level where one would expect some uniformity of vessel diameter in all mammals with red blood cells of comparable size. It is meaningless to define an artery or arteriole on the basis of its diameter, or to define a capillary in this manner. The assignment of a name to a specific vessel should be determined by its position and function in the vascular system.

The most outstanding difference between previously accepted values and those reported here is the determination of that portion of the vascular bed with the greatest total cross-sectional area. If the vascular bed considered in this living animal is acceptable as being representative of peripheral vascular beds, excluding those which serve specific organs, then the greatest total cross-sectional area is formed by the venules rather than by the capillary network.

It is recognized that the number of capillary vessels reported here may be somewhat...
TABLE 2

Measured Capillary Diameters in Various Mammals

<table>
<thead>
<tr>
<th>Animal</th>
<th>Site</th>
<th>Condition</th>
<th>Capillary Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dog</td>
<td>Villus</td>
<td>Injected and fixed</td>
<td>8.0</td>
</tr>
<tr>
<td>Guinea Pig</td>
<td>small intestine</td>
<td>Injected India ink</td>
<td>5.0</td>
</tr>
<tr>
<td>Rabbit</td>
<td>Diaphragm</td>
<td>Injected and fixed</td>
<td>5.0</td>
</tr>
<tr>
<td>Mouse</td>
<td>Heart</td>
<td>Fixed</td>
<td>3.0</td>
</tr>
<tr>
<td>Rabbit</td>
<td>Mesentery</td>
<td>In vivo</td>
<td>5.0</td>
</tr>
<tr>
<td>Guinea Pig</td>
<td>Skeletal muscle</td>
<td>In vivo</td>
<td>5.0</td>
</tr>
<tr>
<td>Human</td>
<td>Diaphragm</td>
<td>In vivo</td>
<td>3.0</td>
</tr>
<tr>
<td>Dog</td>
<td>Heart</td>
<td>In vivo</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*Arranged by dates of publication from Mall in 1888 to Reynolds et al. in 1958.

smaller than is actually the case, and perhaps the vessels referred to as post-capillary vessels should be included with the arterial capillaries in calculations of area and capacity of the network. The fact remains, however, that these are two different types of vessels. The capillary as seen in this preparation is a non-muscular distributing vessel marking the termination of arterial outflow, while the post-capillary venule, with its larger diameter, is truly a collecting vessel returning blood to the venous system.

Summary

Measurements of lengths, diameters, and numbers of post-capillary vessels were made in the bat’s wing. The cross-sectional area and capacity in the various portions of the vascular bed were calculated.

The greatest total cross-sectional area in the entire vascular bed was found in the venous system. This discrepancy probably results from disagreement regarding the diameter of capillary vessels.

Calculations to determine the per cent of total volume in each portion of the vascular bed showed that the venous system accounts for as much as 80% of the total vascular volume.

References

Dimensions of Blood Vessels from Distributing Artery to Collecting Vein
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