Hot-Film Anemometer Velocity Measurements of Arterial Blood Flow in Horses

By Robert M. Nerem, John A. Rumberger, Jr., David R. Gross, Robert L. Hamlin, and Gary L. Geiger

ABSTRACT
Blood velocity measurements were carried out using a constant-temperature hot-film anemometer system in both anesthetized and conscious horses. Catheter probes were used to measure velocity wave forms in conscious horses and L-shaped needle probes inserted by direct vessel puncture were used to measure the profiles in regions of the thoracic and abdominal aorta of anesthetized, open-chest horses. Both catheter and L-shaped probes were used for coronary velocity wave form measurements. The flow conditions were characterized by peak Reynolds numbers of 200-10,000 and unsteadiness parameter of 2-30. These measurements indicate that in the thoracic aorta the flow at peak systole is largely inviscid with a thin-wall boundary layer; in the abdominal aorta the flow is more fully developed but skewed due to branching effects. Highly disturbed flows were observed in the thoracic aorta of both anesthetized and conscious horses, but not in the abdominal aortic region or in the coronary arteries. The results of this study indicate that the flow in the arterial system, although in many cases laminar and disturbance free, is extremely varied in character. It may be asymmetric and certainly is not representative of fully developed, Poiseuille flow.

KEY WORDS
aortic blood flow
Reynolds numbers
hemodynamics
laminar flow
unsteady flow
disturbed flow
velocity profile

Fluid mechanical factors influence the location of sites which show preferential development of arterial disease. For example, both Caro et al. (1) and Fry (2) have identified arterial wall shearing stresses as potentially important factors in the development of atheroma. Although there is some question about the exact role of these fluid mechanical factors (e.g., is it an effect of wall shear on the fluid mass transport or on the properties of the arterial wall), the possible importance of such phenomena requires that more detailed knowledge of the properties of arterial blood flow be gathered.

Recently, point velocity and shear stress measurements within the arterial system have become possible with constant-temperature hot-film anemometer systems. Reports on the use of such systems in the aorta (3-9) agree on the fact that in the ascending and upper descending portions of the aorta a clearly defined aortic wall velocity boundary layer exists. Furthermore, for certain conditions, observations of highly disturbed velocity wave forms have been reported and attributed to the presence of fluid mechanical turbulence in the flow (10).

These in vivo studies have been carried out largely in animals smaller than humans, e.g., dogs and pigs. Limitations on the size of instrumentation have precluded the resolution of certain important flow details in studies on these animals. Thus, there is little, if any, quantitative experimental evidence about the detailed nature of the flow in the aortic wall boundary layer, in the region of branching, and downstream from such branch points. Furthermore, with animals such as dogs and pigs, the observed values of the important flow similarity parameters, e.g., Reynolds number Re = uD/v and the unsteadiness parameter a = R(ω/v)α (u is mean velocity, R is vessel radius, ω is fundamental frequency of the flow pulsations, D is vessel diameter, and v is kinematic viscosity), differ from those associated with the human arterial system (11).

The limiting factor in making measurements of this kind is instrument resolution vs. vessel size. Large horses have aortic diameters in the range of 5 cm, brachiocephalic artery diameters near 3 cm, intercostal and coronary artery diameters of approximately 1 cm, and iliac artery diameters in the range of 1-2 cm. The large size of these vessels...
offers the opportunity of making detailed measurements in numerous vessels with a degree of instrument resolution not possible in smaller species.

Methods

Measurements of velocity wave forms in horses which varied in weight from 136 to 410 kg were made using a constant-temperature hot-film anemometer system with the film held at a temperature approximately 5°C higher than that of the blood. The system used the Disa 55D01 anemometer and the Disa 55D10 linearizer. The principle of operation of hot-film anemometer systems and some of the problems encountered in their use in blood velocity measurements have been discussed in the literature (3).

Catheter probes and L-shaped probes were inserted by direct puncture through the vessel wall. The L-shaped probes were Disa A-87 probes or probes manufactured in our own laboratory (Fig. 1). The catheter probe was also manufactured in our laboratory (Fig. 1). The velocity probes were calibrated during each experiment using blood from the horse. At the start of each experiment, a 200-ml sample of blood was taken, heparin was added to prevent coagulation, and the sample was placed in the calibration turntable channel (12). Here it was maintained at a temperature of 38°C with a thermostatically controlled water heater-circulator system. The probe was immersed in the blood, and by controlling the speed of the turntable channel the probe was calibrated at various known constant velocities. Output signals were passed through the linearizer, which was adjusted to provide a linear output voltage-velocity relationship. Although only a steady-state flow calibration was performed, there have been previous evaluations of the performance of hot-film anemometer systems under unsteady flow conditions. The L-shaped probes manufactured in our laboratory are physically similar to those used by Seed and Wood (3) and thus should have the same frequency response characteristics. For the catheter probes, similar performance characteristics exist for forward flow, i.e., flow coming in over the tip of the catheter; however, for reverse flow the catheter probes are rather unresponsive. The same is true of the Disa A-87 L-shaped probe. None of the probes used in the present series of experiments had a direction capability.

As noted earlier, L-shaped probes were inserted by direct vessel puncture in anesthetized, open-chest horses. Anesthesia was induced with a bolus injection of sodium pentobarbital administered via a catheter previously inserted in the jugular vein. More sodium pentobarbital was administered as indicated. Fluids were administered throughout the experiment in an attempt to inhibit the effects of circulatory shock. For thoracic measurements, the thorax was opened via a left or right thoracotomy with resection of four to six ribs, depending on the exposure required. Abdominal measurements were made via a laparotomy incision from the paralumbar fossa ventral to the midline and cranial to the xiphoid cartilage.

After insertion, the probe was aligned as nearly as possible on a diameter normal to the vessel wall. A micrometer device, which was attached to the probe after puncture of the vessel wall, allowed for graduated changes in probe position. The internal diameter of the vessel at each site was measured by traversing the probe from the near wall to the far wall and adding on the probe width. The probe was then traversed across the vessel in approximately 1-mm steps. Velocity wave forms were thus recorded at a series of positions across the vessel. By keying on the electrocardiogram, the instantaneous velocity profile could then be reconstructed. It should be noted that velocity wave forms were measured repeatedly at the center-line station to check for changes in flow conditions and for probe fouling due to fibrin deposition. If a drift in probe output was noted, the film was wiped gently against the vessel wall to remove any deposition on the sensor surface. In addition, the film cold resistance was repeatedly checked to ensure the repeatability of the velocity

![Diagram of hot-film velocity probes used in this investigation.](image-url)
HORSE ARTERIAL VELOCITY MEASUREMENTS

Circulation Research, Vol. XXXIV, February 1974

probe measurements.

Catheter probes were used to measure coronary artery flow and aortic flow (in conscious animals). For coronary artery flow measurements, the heart was exposed and the pericardial sac opened. The catheter was then inserted in the coronary vessel distal to the region of interest. Prior to insertion of the catheter, the vessel was occluded; it was released by digital manipulation proximal to the area of catheterization periodically over a 5-10-minute period. This procedure was designed to produce some level of tolerance of the myocardium to ischemia. Without this procedure, ligation of the vessel and the sudden onset of ischemia caused cardiac arrest in some animals.

Once inserted, the catheter probe could be easily moved upstream to any position desired. To determine the actual position of the probe at each recording station, a record of how far the probe had been moved from the point of initial insertion was kept. The final probe position was always at the inlet of the coronary vessel within the sinus of Valsalva. After the horse was killed, the probe was kept in position and the heart was excised; visual observation of the final probe position and of the vessel geometry allowed retracing of the other probe positions.

Measurements of velocity wave forms with L-shaped probes were also carried out in coronary arteries. These measurements used the earlier described direct vessel puncture procedure; however, due to the limited vessel size, the only velocity measurements possible were at the approximate midstream of the vessel.

As noted above, catheter measurements of aortic flows in conscious horses were also conducted. The horses were tranquilized with Acepromazine maleate (2 mg/100 lb body weight). The area of the jugular furrow was then instilled with lidocaine HCl 2%, and the jugular vein and the carotid artery were dissected and isolated. The hot-film catheter was taped to a Pieper pressure transducer (13); the tip of the hot-film catheter was located 2 inches proximal to the tip of the pressure transducer. However, the crude wave form obtained was only uncalibrated and that the crude wave form obtained was only used to determine the catheter location. However, the mean arterial blood pressure was estimated to be between 85 and 105 torr. It should also be noted that the tip of the hot-film catheter was located 2 inches proximal to the tip of the pressure transducer.

The measured velocity in the left ventricle (Fig. 2) must be considered qualitative, since the orien-

Results

The present investigation involved four series of velocity wave-form measurements. (1) Catheter measurements were made in conscious horses at selected sites obtained by progressively moving the catheter from an initial position inside the left ventricle in a distal direction to its final position in the carotid artery. (2) Thoracic aorta velocity profile measurements were obtained in anesthetized horses using L-shaped probes inserted by direct vessel puncture. (3) Velocity profile measurements were obtained using L-shaped probes inserted into the abdominal aorta and its branch vessels. Finally, (4) velocity wave-form measurements of coronary flow were made using both catheter and L-shaped probes.

In the first series, aortic flow measurements were carried out in conscious horses. These experiments are summarized in Table 1. Although the catheter was not rigidly positioned in the vessel cross section because of the flatness of the profile (see Figs. 3 and 4), it was felt that the recorded measurements were representative. Included in Table 1 (as well as in subsequent tables) are both the peak center-line velocity (u) and the mean center-line velocity (ü). It is possible to obtain u directly from the measurement. However, ü is an average calculated from the center-line velocity wave form. The probes used were not direction sensitive, and, although a correction for reverse flow was made for those positions at which it was felt to be appropriate, the values of ü must be considered to be only approximate.

Peak aortic center-line flow velocities of nearly 100 cm/sec were obtained in this series of measurements. The corresponding peak Reynolds number Re was on the order of 10,000, and the range of values for the unsteadiness parameter a was 10 to 30. The observed degree of aortic flow disturbance is noted in Table 1. In this table, the flow has been characterized as undisturbed (U), disturbed (D), or highly disturbed (HD) following the definitions in the paper by Nerem and Seed (10). As may be seen, disturbed flows were frequently encountered. Figure 2 shows disturbed flow in a series of measured velocity wave forms for three positions: the left ventricle, just distal to the aortic valve, and the carotid artery. Also shown are the measured pressure wave forms. It should be emphasized that these pressure measurements were uncalibrated and that the crude wave form obtained was only used to determine the catheter location. However, the mean arterial blood pressure was estimated to be between 85 and 105 torr. It should also be noted that the tip of the hot-film catheter was located 2 inches proximal to the tip of the pressure transducer.

The measured velocity in the left ventricle (Fig. 2) must be considered qualitative, since the orien-
TABLE 1

Aortic Flow Measurements in Conscious Horses

<table>
<thead>
<tr>
<th>Horse no.</th>
<th>Position</th>
<th>HR (min⁻¹)</th>
<th>2R (cm)</th>
<th>ȳ / ě</th>
<th>α</th>
<th>Re</th>
<th>Character of flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Left ventricle</td>
<td>76</td>
<td>3.8</td>
<td>48</td>
<td>3.8</td>
<td>29.0</td>
<td>9460</td>
</tr>
<tr>
<td></td>
<td>Ascending aorta just distal to aortic valve</td>
<td>78</td>
<td>3.8</td>
<td>87</td>
<td>3.8</td>
<td>29.0</td>
<td>9460</td>
</tr>
<tr>
<td></td>
<td>Ascending aorta 2 inches distal to aortic valve</td>
<td>83</td>
<td>3.6</td>
<td>62</td>
<td>3.4</td>
<td>28.4</td>
<td>6380</td>
</tr>
<tr>
<td></td>
<td>Arch of aorta 6 inches distal to aortic valve near carotid artery inlet</td>
<td>85</td>
<td>3.0</td>
<td>33</td>
<td>4.0</td>
<td>23.9</td>
<td>2830</td>
</tr>
<tr>
<td></td>
<td>Carotid artery 9 inches distal to aortic valve</td>
<td>93</td>
<td>2.1</td>
<td>16</td>
<td>3.7</td>
<td>17.5</td>
<td>960</td>
</tr>
<tr>
<td></td>
<td>Carotid artery 11 inches distal to aortic valve</td>
<td>79</td>
<td>1.8</td>
<td>8.5</td>
<td>2.8</td>
<td>13.8</td>
<td>437</td>
</tr>
<tr>
<td>2</td>
<td>Left ventricle</td>
<td>67</td>
<td>3.0</td>
<td>93</td>
<td>6.6</td>
<td>14.8</td>
<td>7130</td>
</tr>
<tr>
<td></td>
<td>At aortic valve</td>
<td>33</td>
<td>2.6</td>
<td>53</td>
<td>5.9</td>
<td>14.4</td>
<td>3490</td>
</tr>
<tr>
<td></td>
<td>Ascending aorta</td>
<td>41</td>
<td>2.5</td>
<td>28</td>
<td>5.6</td>
<td>13.7</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>Arch of aorta near inlet to carotid artery</td>
<td>40</td>
<td>1.4</td>
<td>5.0</td>
<td>3.4</td>
<td>7.8</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Carotid artery near incision</td>
<td>42</td>
<td>3.5</td>
<td>87</td>
<td>7.2</td>
<td>18.6</td>
<td>8700</td>
</tr>
<tr>
<td>3</td>
<td>Left ventricle</td>
<td>40</td>
<td>2.7</td>
<td>18</td>
<td>6.0</td>
<td>14.4</td>
<td>1388</td>
</tr>
<tr>
<td></td>
<td>At aortic valve</td>
<td>38</td>
<td>1.7</td>
<td>7</td>
<td>6.3</td>
<td>9.06</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>6 inches distal to aortic valve near inlet to carotid artery</td>
<td>38</td>
<td>1.7</td>
<td>7</td>
<td>6.3</td>
<td>9.06</td>
<td>340</td>
</tr>
</tbody>
</table>

HR = heart rate, R = radius, ě = peak center-line velocity, ȳ = mean center-line velocity, α = unsteadiness parameter, Re = peak Reynolds number, HD = highly disturbed flow, D = disturbed flow, and U = undisturbed flow.

FIGURE 2

Hot-film catheter velocity probe recordings in a conscious horse (no. 1) as the catheter is withdrawn from the left ventricle out into the carotid artery. P = pressure waveform, V = velocity waveform, T = time marks.

The experiments in which thoracic aorta velocity measurements were obtained using L-shaped probes are summarized in Table 2. As noted above, these measurements were performed in open-chest, anesthetized horses in which the probe was inserted by direct vessel puncture. Both the Disa A-87 and the probes manufactured in our laboratory were used. The location of each of the measurements is indicated in Table 2. Because of access limitations, the measurements were carried out in a plane extending through the center of the vessel and perpendicular to the plane of curvature of the aorta. In this series of measurements, peak aortic flow velocities of 90 cm/sec were seen with a
TABLE 2

Flow Measurements in the Thoracic Aorta of Anesthetized Horses

<table>
<thead>
<tr>
<th>Horse no.</th>
<th>Probe</th>
<th>Position</th>
<th>HR (min⁻¹)</th>
<th>2R (cm)</th>
<th>( \bar{u} ) (cm/sec)</th>
<th>( \frac{\bar{u}}{\bar{u}} \alpha )</th>
<th>Re</th>
<th>Character of flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Disa A-87</td>
<td>Descending aorta 7 inches</td>
<td>96</td>
<td>3.05</td>
<td>22</td>
<td>4.4</td>
<td>25.8</td>
<td>1920</td>
</tr>
<tr>
<td>5</td>
<td>Disa A-87</td>
<td>Descending aorta 4 inches</td>
<td>70</td>
<td>2.69</td>
<td>33</td>
<td>5.3</td>
<td>19.4</td>
<td>2536</td>
</tr>
<tr>
<td></td>
<td>Catheter</td>
<td>Descending aorta 5 inches</td>
<td>45</td>
<td>2.41</td>
<td>22</td>
<td>4.0</td>
<td>13.9</td>
<td>1514</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Descending aorta 11 inches</td>
<td>51</td>
<td>2.08</td>
<td>70</td>
<td>3.0</td>
<td>12.8</td>
<td>4160</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Descending aorta 15 inches</td>
<td>59</td>
<td>1.40</td>
<td>96</td>
<td>2.8</td>
<td>9.29</td>
<td>3840</td>
</tr>
<tr>
<td>7</td>
<td>L-shaped</td>
<td>Descending thoracic aorta 4 inches</td>
<td>45</td>
<td>2.5</td>
<td>33</td>
<td>3.8</td>
<td>14.5</td>
<td>2357</td>
</tr>
<tr>
<td>8</td>
<td>L-shaped</td>
<td>Descending thoracic aorta 5 inches</td>
<td>80</td>
<td>2.6</td>
<td>23</td>
<td>2.4</td>
<td>20.1</td>
<td>1709</td>
</tr>
<tr>
<td>9</td>
<td>L-shaped</td>
<td>Descending thoracic aorta 6 inches</td>
<td>51</td>
<td>2.5</td>
<td>33</td>
<td>3.5</td>
<td>15.44</td>
<td>2357</td>
</tr>
</tbody>
</table>

See Table 1 for abbreviations.

*Horse was in shock.

corresponding Reynolds number of 4,000 based on diameter. The range of values of the unsteadiness parameter was from 10 to 25. The estimated ratio of peak velocity to mean velocity ranged from 2.5 to 5.5. This finding is reasonably consistent with the measurements in Table 1 and with measurements in dogs (14).

In selected horses complete velocity profiles were obtained as a function of temporal position in the cardiac cycle. Representative measurements of such a series of velocity profiles in the thoracic aorta are shown in Figures 3 and 4. These profiles are based on averaging over ten cardiac cycles at each station across the vessel lumen. As the probe is moved sequentially across the vessel, the time of a measured velocity during the cardiac cycle is obtained by keying on the peak of the R wave in the electrocardiogram. The finite width of the probe prevented any measurements in the immediate region of the near wall. As a result, it was not always possible to obtain measurements in the near-wall boundary layer. In Figure 3 only measurements in the far-wall boundary layer are included. Thus, in this figure the apparent asymmetry is due to the absence of any near-wall boundary layer measurements. In Figure 4, portions of both the near- and far-wall boundary layers are evident, and no noticeable skewing is present. These measurements were made distal to the aortic arch and not...
The third series of measurements was carried out in the region of the abdominal aorta using L-shaped velocity probes inserted by direct vessel puncture. These measurements are summarized in Table 3. Velocity profiles were obtained in the abdominal aorta proximal to the mesenteric artery, between the mesenteric and renal arteries, and distal to the point at which the renal artery branches off. Profiles were also measured in the terminal aorta and the internal and external iliac arteries. In the horses used, the distal aorta usually gave off paired external iliac arteries which bifurcated within 1–3 cm into the internal iliac arteries. In addition, limited velocity wave-form measurements were obtained in the mesenteric and renal arteries themselves.

Profile measurements in the abdominal aorta were also obtained by sequentially moving the velocity probe across the vessel, keying on the electrocardiogram to reconstruct the velocity profile. Velocity profiles measured in this manner are shown in Figures 5–8. It should be emphasized that many more profiles were measured and that Figures 5–8 have only been selected as representative examples. Included in each figure is a center-line velocity wave form; the time corresponding to the associated velocity profiles is indicated on each wave form. As is obvious, these profiles are different in character with respect to each other and to the thoracic aorta profiles of Figures 3 and 4.

These differences will be discussed in the next section; however, it is obvious that the flow is in many cases complex and certainly not indicative of fully developed Poiseuille flow. From the center-line velocity wave form, the peak Reynolds number $Re$ (based on the peak center-line velocity $u$), the ratio of peak center-line velocity to mean center-line...
See Table 1 for abbreviations.

*Animal was anoxic throughout experiment.

velocity \( \bar{u} \) and the unsteadiness parameter \( \alpha \) can be calculated. This information is included in Table 3; however, compared with those for the thoracic aorta, the peak Reynolds numbers are lower, the unsteadiness parameter values are smaller, and the value of \( \bar{u} / \bar{u} \) is in some cases considerably less.

The final series of measurements was carried out in the right and left coronary arteries with both the catheter and the L-shaped probe. These measurements are summarized in Table 4, and typical wave forms are shown in Figure 9. The apparent difference in wave forms may be partially explained by the difference in heart rate and the condition of the preparation at the time of measurement. Maximum peak velocities of 50-60 cm/sec were measured. The corresponding maximum value of the peak Reynolds number was approximately 1,500, and the range of values for the unsteadiness parameter was 1.5 to 4.0. The estimated ratio of peak velocity to mean velocity ranged from 1.5 to 3.

In Figure 9a a double wave form per cardiac cycle is apparent; it is believed that both wave forms correspond to forward flow (the catheter probe is not direction sensitive). The first hump is associated with systole and the second with diastole. Assuming that both humps correspond to forward flow, then a mean velocity can be calculated. The resulting values are indicated in Table 4. Of course, these measurements must only be considered as representative, since the exact position of the probe in the vessel cross section was not known.
Discussion

From the measurements performed in this series of in vivo experiments in horses, a more complete picture of the general nature of the blood flow in the aorta and the larger arteries is available. This picture obviously is partially due to the results of previous investigations. However, as noted in the introduction, the large size of the vessels of a horse provided an access and a resolution not afforded by the use of smaller animals, and thus the present measurements provide some unique results which in some cases are a verification of what before could only be suspected.

Starting with the left ventricle and its filling process, it is clear from Figure 2 that the flow in this chamber has a reasonably high velocity and considerable high-frequency content. As noted in the previous section, the orientation of the catheter probe and the flow within the ventricle is not known in these measurements in conscious horses. Since differences in probe orientation can cause a change in the calibration characteristics of as much as a factor of two, the peak velocities measured may range from a low of 30 cm/sec to the indicated value in Figure 2 of approximately 60 cm/sec.

The high-frequency content is of interest,
because these disturbances are undoubtedly convected into the aorta itself and are thus important to an understanding of the nature of and the conditions necessary for the presence of highly disturbed aortic flows. Observations of such flows have been reported by several investigators (4-6) and have been considered in detail (10). They have also been observed in the present study, as is illustrated in Figure 2 by the velocity wave-form measurement 1 inch distal to the aortic valve.

In addition to this possible presence of high-frequency disturbances, the most striking feature of the flow in the thoracic aorta is the flatness of the profile in the center region of the vessel. Such a profile is illustrated for the aortic arch in Figures 3 and 4, where the flow can be seen to be characterized by an inviscid core and a thin-wall boundary layer region to which viscous effects are by in large confined. Based on steady-state pipe flow data and for the Reynolds numbers characterizing the mean aortic flow (15), the entrance length, i.e., the distance required for a fully developed viscous flow to be attained, would be approximately 30-40 tube diameters. The thoracic aorta measurements of Figures 3 and 4 were performed within 15 cm of the aortic valve (3-5 tube diameters), and thus the presence of an inviscid core and a thin-wall boundary layer was not surprising. The nature of the boundary layer, of course, must be a combination of the properties due to a steady-state mean flow and to the unsteady, pulsatile flow. In terms of unsteady effects, for pulsatile flow in an infinite cylindrical tube, the viscous effects in the limit of $\alpha$ becoming large are confined to a thin-wall boundary layer (16). Thus, this effect also would suggest that the velocity profile should appear as it is shown in Figures 3 and 4. This finding also has been suggested by the measurements in dogs (4-6).

As noted in the previous section, the measurements in Figures 3 and 4 were not performed in the plane of aortic arch curvature, and thus no skewing due to a curvature effect, such as found by Seed and Wood (6), was anticipated. It should also be noted that, although the peak velocities in Figures 3 and 4 may appear low, this fact is undoubtedly due to the condition of the horse, e.g., the effects of anesthesia and trauma. As may be seen in Table 2, varying peak center-line velocities were recorded.
By comparing with Table 1, it can be seen that the higher values correspond to the conditions in conscious horses. It is felt, however, that, in terms of the profiles shown in Figures 4 and 5 and in subsequent figures, the important thing is the qualitative nature of the velocity profiles and not the exact quantitative value of the velocity.

A similar flat profile to that in the thoracic aorta region is seen in Figure 5 for the flow just proximal to the point at which the mesenteric artery branches off of the abdominal aorta. The high velocity at this point is in marked contrast with that observed in the aorta of the same horse distal to the point at which the renal artery branches off. In this particular animal (horse 13), the mesenteric and renal arteries branched almost immediately adjacent to one another; the large diversion of blood into these branches thus resulted in low velocities at distal points in the abdominal aorta and also in the iliac arteries. Although the velocity profile in the mesenteric artery could not be resolved because of the small vessel size, an approximate midstream velocity wave form was recorded; this wave form is compared in Figure 10 with centerline wave forms for the aorta, both proximal to the mesenteric artery and distal to the renal artery, and for the external iliac artery. As is evident, the higher velocities are observed proximal to the point at which the mesenteric artery branches off and in the mesenteric artery itself.

It has already been noted that distal to the point at which the renal artery branches off the velocities are sharply reduced from those further upstream in the aorta. However, of more interest is the fact that the profiles in this region are no longer necessarily flat but demonstrate a more fully developed viscous flow character. In addition, there is a skewing of the profile which is illustrated in Figure 6 and is believed to be associated with the effects of the branching off of the mesenteric and renal arteries. The profile shown in Figure 6 was obtained in a plane such that the near wall was closer to the side from which the renal artery branched off than it was to the far wall side, and the skewing is believed to be associated with the development of a new boundary layer distal to the renal artery branch point. Thus, though the velocities are relatively low in this region, there appear to be marked profile characteristics associated with branching effects.

Within 10–20 cm (depending on the size of the horse) of the point at which the renal artery branches off, the abdominal aorta then branches into the iliac arteries. As illustrated in Figures 7 and 8, the profiles in the external iliac artery and in the terminal aorta just prior to the branching off of the internal iliac arteries are characterized by the same low velocities seen in the abdominal aorta just proximal and by profiles indicative of a somewhat fully developed viscous flow. The terminal aorta profile is of particular interest because the velocity on the center line is much lower than that in the region further out near either wall. This finding was observed in several horses, but it was most noticeable in horse 11 in which, because of the high heart rate, the velocities and thus the Reynolds numbers were reduced. Comparing the terminal aorta profile measured in horse 12 with that measured in horse 11 (Fig. 8), it appeared that in the former the dip in the profile in the center was not as marked. Horse 11 also had higher Reynolds numbers, and the suggestion of a decrease in the center-line dip with increasing Reynolds number and the general shape of these profiles is in agreement with previously reported measurements in branching air flows (17).
It was noted previously that disturbed flows were observed in a number of experiments. These observations were in the thoracic aorta of both conscious and anesthetized horses. High-frequency disturbances were not observed in the coronary arteries or the abdominal aorta and its branch vessels. However, no measurements in conscious horses were performed in these vessels, and thus no definite conclusions can be stated. Low-frequency disturbances on the order of 5–10 Hz were observed in the abdominal aorta distal to the renal artery branch point in certain horses. This flow appears to be laminar with a low-frequency oscillation which may be the result of complexities associated with the bifurcation at the renal artery branch point, e.g., a shed vortex, and thus not indicative of fluid mechanical turbulence.

As is apparent from the data in Tables 1–4, the flow conditions corresponding to the present measurements cover a wide range. Considering the two basic fluid mechanical parameters—peak Reynolds number Re and unsteadiness parameter \( \alpha \)—the range of conditions encountered in the present experiments includes peak Reynolds numbers ranging from 200 to 10,000 and unsteadiness parameter values ranging from 2 to 30. Associated with these widely different conditions were markedly different velocity wave forms, velocity profiles, and flow disturbance characteristics. It is obvious from these results that the flow in the arterial system, although in many cases laminar and disturbance free, is extremely complex in character. Further studies will provide additional insight into the details of these fluid mechanical characteristics, and it appears that the horse, because of the size of its vessels, offers itself as an excellent experimental animal for such studies.

References

Hot-Film Anemometer Velocity Measurements of Arterial Blood Flow in Horses
ROBERT M. NEREM, JOHN A. RUMBERGER, Jr., DAVID R. GROSS, ROBERT L. HAMLIN
and GARY L. GEIGER

Circ Res. 1974;34:193-203
doi: 10.1161/01.RES.34.2.193

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1974 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
http://circres.ahajournals.org/content/34/2/193