Flow Patterns in the Dog Descending Aorta under a Steady Flow Condition Simulating Mid-Systole

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Hemodynamic factors are suspected to be involved in the localized pathogenesis and development of atherosclerotic lesions in the human thoracico-abdominal aorta. Hence, we studied the detailed flow patterns and the distributions of fluid velocity and wall shear stress there under the condition of a steady flow using five transparent aortic trees prepared from dogs as models of the human descending aorta and by means of flow visualization and high-speed cinemicrographic techniques. It was found that in all the cases the flow in the descending aorta was not fully developed to the extent to provide a parabolic velocity profile. Flow was disturbed at each junction, and most complex secondary and adverse flows formed at the branching site of the left renal artery adjacent to the lateral and posterior walls of the descending aorta. Furthermore, there was considerable interaction between the secondary and adverse flows formed at the branching sites of the four major arteries that stemmed off the descending aorta.

Key Words: Dog Descending Aorta, Flow Pattern, Flow Disturbance, Velocity Profile, Wall Shear Stress

1. Introduction

It has been reported that the descending aorta is one of the most susceptible sites for atherogenesis in humans. The precise location of atherosclerotic lesions are identified to be the proximal lip of the orifice at each branching site of the major arteries stemming from the descending aorta, and the posterior wall of the aorta(1)–(5). These are the regions where flow is likely to be disturbed by the formation of secondary and adverse flows. Hence, to elucidate the relationship between blood flow and the sites of atherogenesis, a number of flow studies have been carried out using various models and casts of the descending aorta of humans and experimental animals(6)–(12). In most cases, studies were focused on identifying the regions of high and low wall shear stress (hence wall shear rate) by measuring velocity distributions. The results of some of these studies suggested that there is a positive correlation between the preferential sites of atherogenesis and the regions exposed to disturbed flows where wall shear stresses are low. However, some of the work was carried out with models which did not take into account the effect of the entrance flow from the left ventricle into the ascending aorta, and its modification in the aortic arch, on flow patterns downstream in the thoracic and abdominal aorta. It was assumed that the straight portion of the thoracic aorta is long enough to provide a fully developed flow with an axisymmetric parabolic velocity profile at peak systole.

To avoid the shortcomings of previous model studies, the present work was carried out using pressure-fixed transparent dog aortic trees, containing the whole heart and eight major branches. The present work is an extension of our previous studies(13), (14) in which the flow patterns in the aortic arch and at some branching sites of the abdominal aorta were investigated to confirm the finding of glass model studies(15), and focuses on detailed flow patterns at each branching site of the four major arteries of the thoracico-abdominal aorta which could not be shown by other investigators.
2. Materials and Methods

Five transparent aortic trees containing the whole heart and eight major branches (brachio-cephalic, subclavian, celiac, superior mesenteric, right and left renal, right and left common iliac arteries) were prepared from adult mongrel dogs (weighing 15 – 30 kg) using a technique previously described\(^\text{(13)}\). Flow studies were carried out at room temperature (23 ± 2°C) using a very dilute suspension of a mixture of 50, 80, 115, 230, and 330 µm-diameter polystyrene microspheres (density \(\rho_s = 1.06 \text{g/cm}^3\), Duke Scientific, Palo Alto, Calif., USA) in methyl salicylate containing ethanol at 5% by volume (density \(\rho = 1.16 \text{g/cm}^3\), viscosity \(\mu = 0.026 \text{g/cm sec}\)) as a substitute for blood. After the aortic tree and the entire flow system were filled with the suspension, the fluid was subjected to steady flow through the aortic tree, and the flow rates in the ascending aorta and eight major branches of the aortic tree were set to their desired values by adjusting the height of the head tank and each collecting reservoir. The volume flow rate in the thoracic aorta just proximal to the branching site of the celiac artery, \(Q_o\), was adjusted to approximately 1 500 mL/min, giving an inflow Reynolds number \(Re_o = D_o \overline{U} / \mu = 1 300\), where \(D_o\) and \(\overline{U}\) are the respective diameter of the thoracic aorta and mean fluid velocity evaluated just proximal to the branching site of the celiac artery, and \(\rho\) and \(\mu\) are the density and viscosity of the fluid, respectively. The flow rate in each branch was set approximately equal to its geometric flow rate ratio (flow rate ratio calculated by assuming that the fluid in the parent vessel is distributed into the daughter vessels in proportion to their cross-sectional areas assessed at the apex of the flow divider). The actual fractions of the flow (expressed in terms of \(Q_i/Q_o\)) which entered each of the four major side branches of the thoraco-abdominal aorta were 0.23 for both celiac and superior mesenteric arteries, 0.15 for both right and left renal arteries, and 0.10 for both the right and left common iliac arteries. For the purpose of presenting flow patterns and velocity profiles at each branching site in the figures, flow conditions specific only to that particular branching site are shown. As in previous studies, flow was visualized using dilute suspensions of tracer microspheres and filming their flow behavior from two different angles in order to deduce three-dimensional flow patterns and distributions of axial fluid velocity and wall shear stress. Further details of the procedures for the flow study, filming and analysis are given in our previous paper\(^\text{(13)}\).

Here we know that both the flow rate in the aorta and the flow rate ratio between the aorta and side branch vary in response to the change in physiological state. For example, during strenuous exercise, the heart increases its cardiac output as much as four to six-fold\(^\text{(16)}\). However, the flow rates in the four major side branches of the thoraco-abdominal aorta markedly decrease because of the increase of the flow rate in the common iliac artery at the expense of a drastic reduction of the visceral flow rate\(^\text{(17)}\). By contrast, under postprandial conditions, the flow rate in both the celiac and superior mesenteric arteries increases by 140% of that in the resting state\(^\text{(18)}\). Such changes in flow rate in the aorta and branch-to-trunk flow rate ratio must affect the flow patterns at each branching site of the descending aorta. Hence we have studied not only flow patterns, velocity distributions and wall shear stress, but also the effects of Reynolds number and branch-to-trunk flow rate ratio on the extent of flow disturbance at the branching site of the renal arteries. The extent of flow disturbance was quantified by measuring the axial length of the adverse flow that was formed adjacent to the lateral and posterior walls of the abdominal aorta from the flow divider of the left renal artery.

In the present study, most of the flow experiments were carried out in steady flow since it is not practical to express the detailed flow patterns observed in pulsatile flow in two-dimensional figures. Only a few experiments were carried out in weak pulsatile flow (steady plus oscillatory flow) with an oscillatory frequency of 2 Hz and displacement volume of 1.5 mL to find out whether the phenomena observed in steady flow also occur in pulsatile flow.

3. Results

3.1 Geometric structure of the dog thoraco-abdominal aorta

Figure 1 shows a photograph of the thoraco-abdominal portion of one of the transparent dog aortas prepared and used in the present study. As shown in the figure, the diameter of the aorta decreased stepwise distal to each branch of the celiac and superior mesenteric arteries. Mean diameters of the aorta proximal to the branching site of the celiac artery, in between the su-

![Fig. 1 Photograph (a left lateral view) of the abdominal aorta of an isolated transparent dog aortic tree showing the geometrical arrangement of the four major branches, i.e., the celiac, superior mesenteric, right renal and left renal arteries. The aortic tree was suspended in a glass chamber filled with oil of wintergreen containing ethanol by 5% by volume. Note that the orifice of both renal arteries are located on the antero-lateral wall of the abdominal aorta.](image-url)
perior mesenteric artery and right renal artery, and distal to the branching site of the left renal artery obtained from the five transparent aortic trees prepared in the present study were 10.5 ± 0.7 (S.D.) mm, 10.2 ± 0.7 mm, and 8.3 ± 0.5 mm, respectively. Mean diameters of the celiac, superior mesenteric, and right and left renal arteries were 5.5 ± 0.2 (S.D.) mm, 5.3 ± 0.5 mm, 4.0 ± 0.3 mm, and 4.3 ± 0.4 mm respectively. Branching intervals, expressed in term of the axial distance between the flow dividers of two neighboring branches, varied greatly from one aorta to another. Measured values varied from 11.8 to 22.4 mm between the celiac and superior mesenteric arteries, from 18.9 to 31.4 mm between the superior mesenteric and right renal arteries, and from 8.2 to 15.4 mm between the right and left renal arteries. The branching angle at the aorto-celiac artery junction was in general much smaller than that at the aorto-superior mesenteric artery junction as shown in Figs. 2 and 3. However, both arteries eventually extended perpendicularly from the anterior wall of the abdominal aorta to the aorta, their median planes becoming common with that of the aorta (c.f. Fig. 1). The branching angles of the right and left renal arteries were approximately 60°, and the branches extended at angles smaller than 90° towards each side from the right and left antero-lateral walls of the aorta. The radii of curvature of the vessel walls at the leading edge of each branching artery opposite to the flow divider were large (e.g. 9.5 mm at the aorto-celiac artery junction, c.f. Fig. 2) while those at the flow divider were small (much less than 1 mm at the aorto-celiac artery junction shown in Fig. 2).

3.2 Flow patterns, velocity distributions and wall shear stresses

3.2.1 The region containing the aorto-celiac artery and aorto-superior mesenteric artery junctions

Flow patterns observed in the aortic segment containing the aorto-celiac and aorto-superior mesenteric artery junctions were very complex, in part due to the fact that disturbed flows formed at the aorto-celiac artery junction strongly affected the flow patterns at the aorto-superior mesenteric artery junction located right distal to it. Fig-

![Fig. 2 Detailed flow patterns (a) and distributions of axial fluid velocity (b) observed in steady flow in the common median plane of the aorta and celiac and superior mesenteric arteries (a left lateral view), in an aortic tree with a large branching interval between the celiac and superior mesenteric arteries. The drawings that were constructed by tracing the paths of tracer microspheres show the formation of an adverse flow along the posterior wall, and spiral secondary flows along the bilateral walls of the abdominal aorta. Distribution of the axial fluid velocity and wall shear stress show a flat velocity profile at the entrance region and low shear regions along the posterior wall and the proximal lip of each orifice. Solid lines represent the paths of particles located in or close to the common median plane; short dashed lines represent paths far out of the common median plane; long dashed lines, or dash-dotted lines represent paths located between the first two types of paths. Arrows at “S” and “P” indicate separation and stagnation points, respectively. Numbers along the velocity profiles indicate the maximum velocity at each cross-section. Numbers at the outside and inside of the vessel indicate the inner diameter of the vessel and wall shear stress measured at each location, respectively. Numbers along the particle paths indicate particle translational velocities (mm/sec) at positions shown. Numbers below \( Q_i \) (\( i \geq 1 \)) at the distal end of each branch and of the outlet indicate the flow rate ratio for each branch to the inflow rate (\( Q_o \)). The following parameters were assessed at the aorta proximal to the orifice of the celiac artery, \( Re_o \): Reynolds number, \( D_o \): vessel diameter, \( Q_o \): volume flow rate, \( \bar{U} \): mean fluid velocity]
Fig. 3 (a): Detailed flow patterns, as in Fig. 2, in an aortic segment containing the aorto-celiac and its adjoining aorto-superior mesenteric artery junction. The thin-layered spiral secondary flows located at the posterior and bilateral walls are closer together. (b): Distributions of axial fluid velocity and wall shear stress, showing a blunted velocity profile in the entrance region and low shear stress at the anterior wall of the aorta juts proximal to the orifice of the celiac artery due to the increase in diameter of the abdominal aorta.

As illustrated in Fig. 2 (a) by the tracings of the particle paths, strong deflection of the flow at each flow divider and separation of the mainstream from the vessel wall occurred at a location indicated by a letter S in the figure, creating a region of separated flow distal to it.

(ii) Secondary flows which entered directly into the celiac artery: Fluid elements located adjacent to the vessel wall of the aorta traveled laterally along the vessel wall encircling the mainstream and entered directly into the region of separated flow at the leading edge of the celiac artery as shown by the short dashed lines, becoming as a part of the double helicoidal flow which was formed in the celiac artery.

(iii) Secondary flows which were formed as a result of flow deflection at the flow divider of the celiac artery: Fluid elements located slightly away from the common median plane, and close to the flow-dividing streamlines which end at the stagnation points (stagnation line) along the ridge of the flow divider of the celiac artery, were deflected laterally and almost at right angles, to the mainstream after which they split into several groups. Some of the fluid elements traveled slowly along the left and right walls of the aorta towards the posterior wall, thus encircling the mainstream as shown by the short dashed lines. They then changed their direction and either flowed down the aorta describing a spiral pattern after executing one large orbit, or entered the superior mesenteric artery where they formed a part of a double helicoidal flow similar to that formed in the celiac artery. Others flowed back very slowly describing large and small saddle-shaped orbits as illustrated by the short dashed lines encircling the mainstream, and then entered the region of separated flow at the leading edge of the celiac artery, joining the secondary flows from the aorta described in (ii) above and eventually forming a double helicoidal flow in that artery.

(iv) Secondary flows deflected at the flow divider of the superior mesenteric artery: Fluid elements located slightly away from the common median plane and close to the flow-dividing streamlines which end at the stagnation points (stagnation line) at the flow divider of the superior mesenteric artery, were deflected laterally almost at right angles to the mainstream, and either entered the branch or traveled along the left and right antero-lateral walls towards the posterior wall of the aorta, as illustrated by the short dashed lines in the figure. Of those, the fluid elements that traveled along the left and right walls and did not flow backwards, met at the posterior wall of the aorta distal to the flow divider of the superior mesenteric artery. Others traveled in large outer orbits, reaching the posterior wall where they changed direction and flowed backwards along the posterior wall, and then changed direction once more and joined the paired spiral flows formed in the
aorta. The fluid elements which were deflected at the flow divider and entered the superior mesenteric artery traveled along the left and right walls of the artery encircling the mainstream in the branch and filled the region of separated flow formed at the leading edge of the superior mesenteric artery. Some of these flowed backwards along the vessel wall, then changed direction and joined the mainstream in the branch. Others formed a double helicoidal flow similar to that formed in the celiac artery.

(v) Intermediate flow which was incorporated in the recirculation zone along the posterior wall: Fluid elements located slightly away from the common median plane and close to the posterior wall of the proximal aorta, indicated by the dash-dotted lines, were directly drawn into the region of separated flow along the posterior wall and flowed backwards in the median plane towards the separation point indicated by the letter S as shown by the solid lines. They then suddenly changed their direction and rejoined the mainstream in the aorta. Due to the formation of the adverse flow and paired spiral flow along the posterior wall of the aorta in and distal to the branching site of the celiac artery, the mainstream located in and very close to the common median plane of the aorta and the two branches was pushed away from the posterior wall towards the anterior wall.

Although the flow in the region of the aorto-celiac and aorto-superior mesenteric artery junctions was classified into five major components as described above, the five types of flows were in fact connected to each other by thin-layered intermediate flows, forming one whole complex flow patterns in this region.

Figure 3 (a) shows another example of flow patterns in the region of the aorto-celiac and aorto-superior mesenteric artery junctions observed in a vessel whose branching interval between the celiac and superior mesenteric arteries was shorter than that of the vessel shown in Fig. 2 (a). As it is evident from the figure, flow patterns observed in this vessel were essentially the same as those shown in Fig. 2 (a). However, the saddle-shaped spiral secondary flows and paired spiral flows occupied more space in this case, squeezing the mainstream towards the anterior wall of the aorta.

Figures 2 (b) and 3 (b) show the velocity distributions and wall shear stresses in the common median plane of the aorta and the two branches. As it is evident from the figures, the velocity distributions in the aorta were flattened in both vessels. This was true in all other vessels studied. In passing through the junction region, the velocity distributions became skewed towards the anterior wall of the aorta where the two arteries branched off. This was because a large volume of fluid was taken by these two branches and mainstream shifted towards the anterior wall. Velocity distributions in the branches were skewed towards the inner wall on which the flow divider is located. As expected from the flow patterns shown in Figs. 2 (a) and 3 (a), the values of wall shear stress were much smaller at the posterior wall of the aorta than those at the anterior wall.

3.2.2 The region containing the aorto-renal artery junction Flow patterns and velocity distributions in the region containing the right and left renal artery junctions as observed from three different directions are shown in Figs. 4–6. In Fig. 4, the flow was observed from a direction normal to the common median plane of the left renal artery and the abdominal aorta (a left posterior oblique view). In Fig. 5, the same flow was observed from a direction normal to the mid plane (sagittal plane of the body) extending from anterior to posterior wall (a left lateral view). In Fig. 6, the flow was observed from a direction normal to a plane extending from right to left wall (a postero-anterior view).

At first sight, the flow patterns observed normal to the common median plane of the left renal artery and the aorta (shown in Fig. 4 (a)) appeared to resemble those observed previously in 90° glass model T-junctions(15), in which a paired thin-layered saddle-shaped spiral secondary flow was formed adjacent to the tube wall encircling the mainstream. In the present case of the abdominal aorta, however, the mainstream was drawn towards the anterior wall by the flow entering the celiac and superior mesenteric arteries. Thereafter, the flow attempted to expand again towards the posterior wall of the aorta. However, this expansion did not occur symmetrically due to the presence of the flow entering the right renal artery, causing the mainstream to be skewed towards the right anterior wall. Hence, the thin-layered spiral secondary flows was not paired but single and located mainly along the left posterior wall of the aorta as it can be seen in Figs. 5 (a) and 6 (a). In addition to this, there was a marked interaction between the disturbed flows formed at the junctions of the right and left renal arteries. Along the right posterior wall distal to the junction of the right renal artery, the mainstream remained detached from the wall, and the region was occupied by a spiral secondary flow which had its origin in flow deflection at the flow divider of the superior mesenteric artery (c.f. Figs. 2 (a) and 3 (a)) and reinforced by the deflection of flows at the flow divider of the right renal artery (c.f. Figs. 5 (a) and 6 (a)). In contrast to this, along the left posterior wall, the mainstream reattached to the vessel wall proximal to the junction of the left renal artery (c.f. Fig. 4 (a)). As shown in Fig. 5 (a), a large thin-layered spiral secondary flow formed adjacent to the left posterolateral wall of the aorta with separation (S) and stagnation points (P) locating on the posterior wall with its base extending right across the orifice of the left renal artery near the left lateral wall.

As shown by the short dashed lines in Figs. 4 (a) and 5 (a), fluid elements flowing on the left anterior side of
Fig. 4 (a): Detailed flow patterns observed in the common median plane of the aorta and the left renal artery (a left posterior oblique view) showing the formation of a thin-layered, saddle-shaped spiral secondary flow along the postero-lateral wall of the abdominal aorta at the left aorto-renal artery junction. (b): Distributions of axial fluid velocity and wall shear stress showing that wall shear stress is higher at the inner wall of the aorto-renal artery junction. Solid lines represent the paths of particles located in or close to the median plane; short dashed lines represent paths far out of the median plane; long dashed lines or dash-dotted lines represent paths located between the first two types of paths. Arrows at “S” and “P” indicate separation and stagnation points, respectively. Numbers along the velocity profiles indicate the maximum velocity at the cross-section indicated. Numbers at the outside and inside of the vessel indicate the respective inner diameter of the vessel and wall shear stress measured at each location. Numbers along the particle paths indicate particle translational velocities (mm/sec) at positions shown. Numbers below $Q_i$ ($i \geq 1$) at the distal end of the outlet and each branch indicate the flow rate ratio for each branch to the inflow rate ($Q_o$).

mainstream, reaching the posterior wall at, or close to, the stagnation point P. They then changed direction, some circulating in large orbits close to the posterior wall of the infrarenal aorta, and joined the spiral secondary flow in the aorta. Others circulated in smaller orbits close to the orifice of the left renal artery, some entering the branch where they formed a part of a double helicoidal flow.

At the aorto-right renal artery junction, as shown in Fig. 5(a), fluid elements which deviated from the spiral secondary flow formed at the branching sites of the superior mesenteric and right renal arteries traveled along the right lateral wall of the aorta at right angles to and encircling the mainstream. Then upon reaching the posterior wall, they were drawn into the thin-layered spiral secondary flow described above. Some of these circulated in small inner orbits moving back towards the junction region of the left renal artery. Then, upon reaching the proximal lip (leading edge) of the left renal artery, they entered the branch from the leading edge (located on the outer wall (hip)) of the bifurcation. Others circulated in larger outer orbits near the posterior wall of the infrarenal aorta, and then traveled down the left renal artery, forming a part of the double helicoidal flow developed in that branch. Figures 4(b)–6(b) show the distributions of fluid velocity and wall shear stress in three different median planes.
Fig. 6 Detailed flow patterns (a) and distributions of axial fluid velocity and wall shear stress (b) in the same vessel as that shown in Figs. 4 and 5, as observed along the mid plane (postero-anterior view). Drawings show the confluence of secondary flows originating at the flow dividers of the right and left renal arteries. Fluid elements in the inner orbits of the spiral secondary flows flow back along the dorsal wall and finally enter the left renal artery. Note that shear stress is low at the left lateral wall even near the flow divider of the left renal artery.

In the common median plane of the left renal artery and the aorta and in the mid plane, the velocity distributions distal to the orifice of the left renal artery were skewed towards the left anterior wall and the anterior wall, respectively (c.f. Figs. 4 (b) and 5 (b)). In the median plane normal to the mid plane, the velocity distributions were blunted towards the right lateral wall, resulting in low wall shear stresses on the left lateral wall of the infra-renal aorta as shown in Fig. 6 (b). Due to the presence of the spiral secondary flow adjacent to the posterior wall of the aorta in which the fluid elements traveled in a direction opposite to that of the mainstream, wall shear stresses distal to the orifices of the renal arteries were lower on the posterior wall than those on the anterior wall (c.f. Figs. 4 (b) – 6 (b)).

3.3 Factors affecting the size of the adverse flow at the aorto-renal artery junction

As described above, the saddle-shaped thin-layered adverse flow (spiral secondary flows) generated by strong deflection of fluid elements at both flow dividers of the superior mesenteric and right renal arteries as well as at the flow divider of the left renal artery, existed along the left postero-lateral wall of the abdominal aorta just around the orifice of the left renal artery. The length of this adverse flow, as measured from the flow divider of the left renal artery to the downstream stagnation point, P, increased slightly with increasing inflow Reynolds number, \( R_{eo} \), from 770 to 1000, while keeping the outlet-to-inlet flow rate ratio, \( Q_1/Q_o \), constant at 0.5 as shown in Fig. 7. However, as shown in Fig. 8, when \( Q_1/Q_o \) was increased from 0.40 to 0.65 while keeping \( R_{eo} \) constant at 770 to 1000, the length of the adverse flow region decreased drastically.

It was noted that the flow patterns in the thoraco-abdominal aorta were not affected so much by the change in flow rate and branch-to-trunk flow rate ratio, and remained essentially the same as those shown in Figs. 4 – 6.

3.4 Flow patterns observed under conditions of a pulsatile flow

Flow studies were carried out also under the conditions of a pulsatile flow (steady + oscillatory flow) with a displacement volume of 1.5 mL and oscillatory frequency of 2 Hz (Womersley number \( \alpha = 13 \)). Observations of the cine films that recorded the behavior of tracer microspheres revealed that the flow patterns and the locations of the spiral secondary flows were qualitatively the same as those observed in steady flow. It was noted that both the sizes of the spiral secondary flows and adverse flow and the velocity of tracer microspheres during the systolic pe-
period of the pulsation were larger than those in steady flow if they were compared at the same mean Reynolds number.

4. Discussion

We have presented the detailed flow patterns, distributions of axial velocity and wall shear stress in the thoracoabdominal aorta of the dog obtained using isolated and pressure-fixed transparent vessels that maintained the complex three-dimensional geometry of the four major side branches. In the present study, the effect of elasticity of the vessel wall had to be neglected since the vessels became rigid after being fixed and rendered transparent with oil of wintergreen. However, it is reported that the wall of the abdominal aorta is only one third as distensible as that of the thoracic aorta. Therefore the change in the diameter of the abdominal aorta during the cardiac cycle is expected to be relatively small. Studies carried out by some other groups suggested that wall elasticity actually reduces the intensity of flow disturbance, but never changes the flow patterns qualitatively. Thus, we believe that the flow patterns observed in our transparent models of the dog thoracoabdominal aorta would have been close to those existing in vivo under physiological conditions.

The effect of pulsatility on flow patterns is difficult to estimate. To properly study the effects of pulsatility, it is necessary not only to simulate the physiological pulse pressure wave but also the real elasticity of the vessel wall. Since the elasticity of the vessel wall is not isotropic and it is not possible to imitate, the results of several studies do not agree with each other on the effect of pulsatility on flow patterns. Some studies, as do our results, suggest that pulsatility does not change flow patterns qualitatively. Other studies suggest that flow patterns observable under the conditions of a pulsatile flow are essentially different from those observable under the conditions of a steady flow.

In the present study, we prepared the thoracoabdominal aorta as part of a whole aortic tree containing the whole heart, the aortic arch and all major side branches stemming from the aorta in order to mimic the blood flow in vivo under physiological conditions. In this model, we found that the velocity distributions in the thoracic aorta were flattened (c.f. Figs. 2 and 3). There have been some reports which described the results of in vivo measurements of blood flow in the lower thoracic aorta carried out by using hot-film anemometry and MR Imaging and Doppler ultrasound velocimetry. The consensus of these studies is that the flow from the left ventricle never becomes a fully developed Poiseuille flow when it reaches the abdominal aorta. In fact, considering the anatomic structure of the aortic arch, which is curved with two side branches stemming out of it, together with pulsatility of the flow, it is likely that development of a parabolic velocity distribution is retarded. From fluid mechanical considerations, the entrance length, for the development of a parabolic velocity profile in a rigid cylindrical tube is given by the expression . Applying the physiological parameters for the dog thoracoabdominal aorta, the entrance length is calculated to be 72 cm, which is much longer than the length of the thoracic aorta. It thus appears that, to substitute a cylindrical tube for the heart and the thoracic aorta as an inlet to the dog abdominal aorta, as we have done in our preliminary study, may result in flow different from that existing in vivo. It is possible, for instance, that if the velocity distribution proximal to the branching site of the celiac artery were parabolic, it may promote the formation of much stronger and more complex secondary and adverse flows along the postero-lateral wall of the abdominal aorta where four major arteries branches off the aorta.

The five aortic trees which we prepared and used in the present study showed variations in branching interval, but the order of the side branches was always the same. As shown in Figs. 2 and 3, differences in branching interval between the celiac and superior mesenteric arteries did not qualitatively change the flow patterns in the abdominal aorta. Similarly, flow patterns in the lower part of the abdominal aorta, where the right and left renal arteries branched off, were not affected by variations in the branching interval among these aortic trees. These findings lend credibility to our technique of preparation of the aortic trees and to the existence of the flow patterns we...
described.

Detailed analysis of the flow showed that in the region between the branching sites of the celiac and superior mesenteric arteries, the posterior and bilateral walls were exposed to spiral secondary flows formed as a result of strong deflection of flows at the flow divider of these two side branches. Flow patterns were far more complex than those previously observed either in glass model T-junctions\(^{15}\) or in the isolated transparent dog thoracico-abdominal aorta containing only the part of the celiac and superior mesenteric arteries\(^{14}\). Obviously, this was caused by the strong reciprocal interaction between the disturbed flows formed at the two adjacent junctions.

Flow patterns in the lower abdominal aorta, where the right and left renal arteries branched off, were even more complicated than those in the upper abdominal aorta where the celiac and superior mesenteric arteries branched off where the orifices of both the right and left renal arteries were located on the antero-lateral walls and the arteries were curved ventrally. Thus, there was no common median plane of the branches and the aorta, and the velocity distributions in the aorta proximal to these two side branches were already skewed towards the anterior wall. The mainstream in the aorta which was already shifted towards the anterior wall by the formation of an adverse flow along the posterior wall of the upper abdominal aorta, was further shifted first towards the right and then towards the left lateral walls because of the presence of the orifices of the right and left renal arteries on the right antero-lateral and left antero-lateral walls of the abdominal aorta, resulting in the formation of a unique, saddle-shaped spiral secondary flow as shown in Figs. 5(a) and 6(a). These findings suggest that it is the three-dimensional arrangement of the orifices of the four neighboring side branches that characterizes the flow patterns at the junction of the aorto-renal arteries. Moreover, observations of the flow showed that increasing the inflow \(Re\) or the ratio of the outflow to inflow did not qualitatively affect the flow patterns in the lower abdominal aorta.

Studies of the topographic distributions of atherosclerotic lesions formed in the human abdominal aorta showed that the preferred sites are the proximal lip of each orifice and the posterior wall of the abdominal aorta\(^{(1)}\) – \(^{(5)}\). The present study shows that these are the very places where separation of streamlines from the vessel wall, formation of slow spiral secondary and adverse flows occur. If we assume that the flow patterns in the human thoracico-abdominal aorta resemble those in the dog, then the results obtained in the present study strongly suggest that the disturbed flow, which creates the regions of low wall shear stress, is playing an important role in the genesis and development of atherosclerotic lesions. Some investigators consider that the reason why the preferred sites of atherosclerotic lesions are located on the posterior wall of the thoracico-abdominal aorta is due to the presence of the intercostal arteries in the thoracic aorta and the lumbar arteries in the abdominal aorta on the posterior wall\(^{(2)}\). However, the existence of these arteries cannot account for the fact that the lesions are more severe in the region where the four major arteries branch off\(^{(3)}\). The present work could account for this finding. If we assume that flow separation and the resultant formation of regions of low wall shear stress are responsible for the genesis and development of atherosclerosis, it follows from the result of the present work that the distribution of atherosclerotic lesions is largely affected by the geometric structures of the vessels.

Measurements of the length of the adverse flow region distal to the orifice of the left renal artery clearly showed the effect of outlet-to-inlet flow rate ratio and Reynolds number on the extent of the flow disturbance at the aorto-left renal artery junction. Both the range of inflow \(Re\) (700 – 1 050) and flow rate ratio, \(Q_1/Q_o\) (0.40 – 0.65), studied were representative of physiological values in the resting to mild exercise state. It was the change in flow rate ratio that most markedly affected the flow disturbance. During exercise, the ratio of the branch flow rate to that of the aorta decreases (\(Q_1/Q_o\) increases), while \(Re\) increases. According to the results shown in Figs. 7 and 8, this will suppress the extent of the flow disturbance, as previously shown by Ku et al.\(^{(7)}\). In this connection, Zarins and Glagov have suggested that sedentary life promotes the development of atherosclerotic lesions in the human abdominal aorta\(^{(5)}\). It was also shown in the pig, that physical fitness inhibits the development of atherosclerosis in the abdominal aorta\(^{(29)}\). These might be related to the change in the flow rate ratio between the branch and the aorta, reducing the area occupied by the slow adverse flow.

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