The peculiarities of the arterial circulation, including pulsatile flow in tubes with distensible walls and multiple branchings, make it difficult to apply classical hydrodynamic principles to the aortic blood flow without direct experimental verification. An example of the present confusion regarding fundamental concepts is the question of mixing in the aortic root. The generally accepted view is that thorough mixing takes place in this location. Some of the experimental evidence, however, suggests that complete mixing does not occur regularly in any part of the central circulation.

As a substitute for a direct experimental approach, the Reynolds number has been used to predict the type of flow that may occur in various parts of the aorta. It is doubtful that the Reynolds number can be used with confidence to predict whether aortic blood flow will be laminar or turbulent since even with steady flow in rigid pipes the critical Reynolds number may vary greatly depending on local conditions, while the effects produced by pulsatile flow and distensible tubes are unknown.

A few attempts have been made to visualize the distribution of dyes either directly or by cinematography. In view of the difficulties of such visualizations of dyes in the aorta, it is not surprising that the above studies reached different conclusions. The method of sampling simultaneously from multiple arteries following the injections of dyes proximally in the central circulation also is open to question.

Methods

The flow pattern in the aorta was studied by using cold saline solution as the indicator and a thermistor as the detector. The cold saline solution was infused in the direction of flow at a rate of 0.25 ml/sec through PE 205 tubing. At this rate saline entered the aorta without producing a jet. The thermistor, located in the bevel of an 18-gauge "thin-walled" needle, 1 mm proximal to the needle point, was oriented along the diameter of the aorta downstream from the infusion. This location was obtained by inserting the needle in a plane normal to the long axis of the aorta.

The shaft of the hypodermic needle was filed with grooves, spaced at 2 mm intervals, which were coated with black paint to make them easily visible. A Touhy-Borst adapter was attached to the hub of the needle to permit egress of the insulated thermistor lead wires.

The dynamic response of the thermistor was tested as follows: The thermistor was inserted through a rubber stopper into a glass tube containing water at room temperature. A 20-gauge needle also was inserted through the rubber stopper and its hub was attached to a Statham P23D strain gauge. An additional needle was introduced to serve as an overflow drain. The opposite end of the glass tube was closed by a stopper through which a luer connection was inserted. Water cooled to approximately 5°C was injected suddenly into the chamber through the luer connection. Care was taken to position the thermistor directly in line with, and in close

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Dynamic response of thermistor as determined in a test chamber. Baseline to peak temperature drop represents 2.8°C. See text.

approximation to, the jet of cold water injected suddenly into the tube. The thermistor response was compared with the pressure curve. Figure 1 shows that peak temperature response lagged behind the peak pressure response by 0.04 sec. Because of the position of the thermistor in close approximation to the entrance of the jet into the chamber, the observed delay was due to the lag in the thermistor response. The time constant (two-thirds of full response) as determined by dipping the thermistor suddenly in water at 37°C, was 0.03 sec. The above results were consistent with the following observations, made in vivo.

Cold saline solution was injected suddenly during the diastolic interval into the left ventricle of dogs while both temperature and pressure were recorded in the root of the aorta. With the next systolic ejection, aortic temperature began to fall 0.04 sec after the onset of rise of systolic pressure in the aorta.

Twelve mongrel dogs weighing 10 kg to 14 kg were anesthetized with pentobarbital sodium, intravenously, and the left chest was opened with the animal lying on its right side. A catheter made from PE 205 tubing, slightly curved near the end, was inserted down the carotid artery into the descending thoracic aorta. The position of the tip was located by palpation of the aortic wall. The location of the catheter opening in the longitudinal axis of the aorta also was checked by observing the effect on the pressure pulse of brief compression of the aorta above and below the catheter tip. The end of the catheter usually was placed 4 cm to 5 cm distal to the aortic arch in the descending thoracic aorta and, as described below, was withdrawn between periods of infusion, in steps of 1 cm, into the aortic arch. A motor driven syringe (Harvard infusion pump) was used for injecting the cold saline. Several feet of polyethylene tubing, coiled in an ice bath, were interposed between the pump and the infusion catheter in order to maintain the infusate at constant temperature as it entered the catheter. Infusion was started at least 10 sec before beginning temperature recordings. A second catheter used for recording arterial pressure was inserted up the femoral artery to the lower thoracic aorta.

With the bevel of the needle containing the thermistor facing upstream, the descending thoracic aorta was punctured at a point 5 cm to 6 cm below the arch. The needle was advanced across the diameter of the aorta until the point made light contact with the opposite wall. After infusion of cold saline was begun, recordings were made of the temperature and pressure fluctuations. The needle was then withdrawn 2 mm across the diameter of the aorta, the position being obtained by observing the graduations filed on the shaft of the needle. In this manner temperature recordings were made at 2 mm intervals traversing the cross-sectional diameter of the aorta until the bevel of the needle appeared at the point of insertion into the aorta. The needle tip then was advanced again to the opposite inner wall of the aorta, the infusion catheter was withdrawn 1 cm toward the arch and another series of temperature recordings were made across the aortic diameter. This sequence was repeated until the end of the infusion catheter had been withdrawn into the middle of the aortic arch. In early experiments it was found that in some dogs hemorrhage occurred between the layers of the aortic wall after the needle was introduced. The results of experiments following appreciable dissection of the aortic wall were discarded. Dissection was most apt to occur in dogs with aortic
blood pressure above 140/90 mm Hg. In such hypertensive animals dissection was prevented by reducing the blood pressure with hexamethonium, 3 mg/kg, intravenously, prior to inserting the needle.

Cold saline solution was infused into the root of the aorta by inserting a 12-gauge needle beneath the xiphoid and advancing the tip through the apex of the left ventricle. The infusion catheter was inserted through the needle to a point 0.5 cm beyond the aortic valve as determined by observing the change in the pressure pulse recorded through the catheter. The thermistor then was inserted across the diameter of the aorta in the distal third of the arch in some experiments, and in others, in the ascending aorta.

In the studies on retrograde flow and mixing at the base of the aorta following sudden injection, the insulated thermistor leads were enclosed in an injection catheter made from PE 205 tubing containing side holes located 1.5 cm proximal to the thermistor bead. The end of the catheter was tapered to seal off the thermistor from the lumen of the injection catheter. A Y-shaped adapter was used at the opposite end, one arm of which carried the thermistor leads while the other was used either for pressure recording or for injections. The thermistor catheter was inserted either into the femoral artery, the carotid artery, or the left ventricle, depending on the nature of the study. Two ml of cold saline were injected over a period of 0.5 sec using a Brewer pump* operated by a foot switch. Depressing the foot switch closed a relay which marked the time of injection on the record. When two thermistors were used the amplifiers were adjusted so that they provided equal deflections on the recording galvanometers for a given change in temperature. Sanborn thermistor resistance bridges, carrier wave preamplifiers, and optical recording galvanometers were used throughout these studies.

Results

CHARACTER OF FLOW IN THE DESCENDING THORACIC AORTA AND DISTAL ARCH

Flow in the distal third of the arch and descending thoracic aorta appeared streamlined. When the infusion was made near one

* Brewer Automatic Pipetting Machine, Model no. 07-40-SS-50, Baltimore Biological Laboratories, Division of Becton-Dickinson Company, Baltimore, Maryland.

![Diagram](http://circres.ahajournals.org/)

**FIGURE 2**

Temperature (upper trace) at 2 mm intervals traversing the cross-sectional diameter of descending thoracic aorta and pressure (lower trace) are shown on the right. Gain of amplifier adjusted to provide 10 cm deflection for 1° temperature change from 37°C to 36°C. Distance between fine horizontal lines equal 1 mm. Diagrams on left show positions of thermistor (in the bevel of the needle) and of infusion catheter. See text for details.

* Circulation Research, Volume XIV, February 1964
wall of the aorta, the temperatures distal to the infusion site were lowest near that end of the aortic diameter and exhibited the greatest temperature fluctuations during the cardiac cycle. As the thermistor was moved across the aortic diameter toward the opposite wall, the temperature rose and the magnitude of the fluctuations decreased. Streamlined flow continued to be evident when the tip of the infusion catheter was withdrawn to a position 5 cm or 6 cm upstream from the thermistor (fig. 2).

In general, blood temperature fell steeply during early systole, rose sharply during late systole and remained uniformly high in diastole. The steep fall was due to propulsion past the thermistor of cold saline mixed with blood which had accumulated around the infusion catheter during the latter part of the preceding diastole. This was followed in late systole by warmer blood coming from more proximal portions of the aorta which diluted the indicator and produced the sharp rise in temperature.

INDICATOR DISTRIBUTION IN THE ASCENDING AORTA

When cold saline solution was infused in the direction of forward flow in the ascending aorta, the mean temperatures, degree of fluctuation and rate of change of temperature were approximately equal across the diameter of the aorta, both near the walls and in the central stream (fig. 3, bottom panel). The recorded temperature usually fell in early systole, rose in late systole and tended to remain high in diastole, although displaying some irregularity from one cardiac cycle to the next. The flow did not tend to separate into streamlines along the diameter of the aorta even when the thermistor was located in the ascending aorta only 1 cm or 2 cm distal to the site of infusion.

The transition between mixed and streamlined flow of indicator seemed to occur at the origin of the brachiocephalic trunk. With the thermistor located at the isthmus of the aorta, infusion just beyond the brachiocephalic trunk revealed streamlined separation of indicator (fig. 3, top panel). Infusion just proxi-
HYDRODYNAMICS OF AORTIC FLOW

FIGURE 4

Temperature recordings (upper traces) from two thermistors in the ascending aorta placed as indicated in the diagram. Lower trace is aortic pressure. Cold saline was injected suddenly via the catheter protruding through the aortic valve. Period of injection is indicated below the tracing. Note equalization of temperatures with onset of next systole.

Normal to the trunk indicated apparent mixing of the cold saline across the diameter of the aorta.

Additional evidence of mixing in the ascending aorta was obtained using two thermistors, one inserted through a carotid artery, the other through the apex of the ventricle. Each thermistor was mounted in separate injection catheters. They were positioned as shown in figure 4. When 2 ml of cold saline solution were injected suddenly through one of the injection catheters during the diastolic interval, the temperatures recorded by the two thermistors often varied considerably in both direction and magnitude (fig. 4). With the onset of the next systole, however, the temperatures recorded by the two thermistors immediately became equal and remained essentially equal during the succeeding disappearance of the indicator. When the injection was made in systole the temperatures were essentially equal during and following the period of injection. These results indicated that mixing in the ascending aorta occurred primarily in systole.

Apparent nonmixing was recorded when either thermistor was in direct contact with the aortic wall. Such contact was easily detected by a sluggish response of the thermistor to the temperature fluctuations produced by the cold saline. These artifacts could be avoided by positioning the thermistors so as to obtain brisk responses to temperature changes.

SOUND RECORDING IN THE AORTA

Laminar flow is silent whereas disturbed flow frequently generates noise. A catheter-mounted sound transducer* was inserted through a carotid artery in closed chest dogs in order to record the sounds present in various parts of the aorta. The end opening of the plastic cap which protects the diaphragm of the transducer was plugged with Silastic leaving the side holes open. In the distal arch and descending aorta, no sound other than the two heart sounds could be detected. In the ascending aorta, sound waves, predominately 100 to 200 cycles/sec, were recorded during the systolic interval. These sounds, which were of lower intensity than the first and second heart sounds, were most prominent in the root of the aorta and faded out as the

* Dallons Telco Micromanometer.
transducer was withdrawn into the arch (fig. 5).

**BACKFLOW IN THE AORTA**

Backflow was detected by using a thermistor mounted on the injection catheter, as described previously, which was inserted up the femoral artery. The thermistor was located 2 cm upstream from the radially directed injection ports and was sealed off from the lumen of the catheter. Considerable backflow of indicator was present in the abdominal aorta distal to the renal arteries, but none could be detected 2 cm upstream in the abdominal and thoracic aorta between the renal arteries and the arch of the aorta. Backflow again occurred in the region between the root of the aorta and the distal end of the aortic arch.

**CINEANGIOGRAPHIC STUDIES**

Cineangiography was carried out using an 8-inch Picker image intensifier with a 35-mm cineradiography camera and Orthicon.
HYDRODYNAMICS OF AORTIC FLOW
television viewing attachment. The contrast material was 80% sodium iothalamate (Angio-Conray). Kodak Cineflure film was used for these studies. All experiments were done in anesthetized, closed chest dogs lying on their right side. The sodium iothalamate solution was infused through PE 205 catheters in the same manner as described in the studies using thermistors. All motion picture sequences were taken at a speed of 60 frames/sec.

In the descending thoracic aorta streamlined flow was observed during systole and part of diastole. Figure 6 shows selected frames taken during constant infusion of sodium iothalamate at a rate of 0.125 ml/sec. The numbers below each cineangiogram refer to the position of the respective frame in the sequence taken one-sixtieth of a second apart from the beginning of systole to late diastole in a dog with a heart rate of 160 beats/min. Streamlined flow was seen during the period of peak systolic flow (fig. 6, frame 3) and in mid diastole (frame 15). Slight reversal of flow occurred at the onset of diastole (frame 7). Some spreading of the contrast material across the diameter of the aorta was observed during the period of reversed flow as well as in late diastole (frame 20) and onset of systole (frame 1). Thus, the pattern was predominantly laminar during periods of rapid forward flow. During periods of retarded or reversed flow there was partial mix-
ing of indicator across the streamlines.

The distribution of contrast material infused in the direction of flow in the ascending aorta is shown in the upper half of figure 7. The infusion rate was 0.25 ml/sec. Frame 1 was recorded near the end of diastole. Some of the contrast material can be seen in the sinus of Valsalva indicated by the arrow. Indicator was carried to this location during the prominent backflow phase occurring in early diastole. Frame 4 was taken in early systole during the period of rapid acceleration of the aortic blood flow. It can be seen that the streamer of infused contrast material has broken up. The larger portion has moved downstream and at the same time has spread across the aortic diameter in a pattern of irregularly rounded globules. Another portion has been directed backward toward the ostium of the coronary artery. Not apparent in these single frames but visible when projected at rapid film speed was the fact that additional contrast material was considerably diluted by diffuse mixing with the aortic blood flow.

![Figure 7](https://example.com/figure7.png)

**FIGURE 7**

Shown above are cineangiograms taken during constant infusion of sodium iothalamate in the ascending aorta. Frame 1 was taken in late diastole and frames 4 and 5 during early systole. See text for further description. Shown below are cineangiograms taken after sudden injection of contrast material into the root of the aorta. Frame 1 was taken at the end of diastole and frames 3 and 4 in early systole. Note separation of central stream from the layer along the walls of the aorta. See text.
Frame 5 in the sequence shows further spreading of the indicator at the branching of the brachiocephalic artery, the origin of which is indicated by the arrow.

In additional experiments a catheter was inserted into the carotid artery and advanced to the root of the aorta. Five-tenths ml sodium iothalamate solution were injected suddenly during the diastolic interval so that the area just above the aortic valves was mixed with dye.

Frame 1 (fig. 7) was exposed at the end of diastole and frame 3 was taken shortly after the onset of systole as the bolus of contrast material began to move up the aorta. Frame 4, taken during the period of rapid acceleration of flow, shows undyed blood entering the aorta. The majority of the contrast material has moved into the proximal portion of the aortic arch. However, residual indicator has been left along the walls of the ascending aorta as well as in the sinuses of Valsalva. It was apparent that during the phase of rapid acceleration of blood flow there was separation of the central stream from a slower moving layer adjacent to the walls of the ascending aorta as well as from the region behind the valve cusps.

Discussion

The above observations are consistent with the presence of predominantly streamlined but not entirely laminar flow in the distal arch and descending aorta, and with disturbed but not necessarily turbulent flow in the proximal arch and ascending aorta. The mixing which occurs at the root of the aorta appears to be due primarily to certain anatomical features of this region which influence the viscous forces acting on the flow.

The aortic root is characterized by a narrow inlet, the valve orifice, projecting into a tube of considerably larger diameter, the aortic bulb. A pipe of increasing diameter, called a diffuser in hydrodynamic terminology, promotes mixing of the fluid which flows through it. The more abruptly the pipe widens out the more complete the mixing will be. Such mixing occurs as follows: through the conversion of kinetic to potential energy, the pressure increases in the wider portion of the tube as the velocity decreases. The fluid in the boundary layer near the wall, therefore, is moving against a pressure gradient. The motion of the fluid inside the boundary layer is determined by three factors: it is retarded by friction at the bounding wall; it is pulled forward by the stream above it through the action of viscosity; and it is retarded by the adverse pressure gradient. The fluid near the wall is brought to rest and further on a slow backflow in the direction of the pressure gradient sets in. The forward stream then leaves the wall forming a jet. Such separation of flow in the ascending aorta was seen in the cineangiograms (lower half of fig. 7). The more rapid the expansion of the pipe, the more abruptly the effect occurs. When there is, in addition, a sharp edge over which the flow must pass, such as the edge of the valve leaflets, separation occurs immediately at the edge and almost instantaneously at the beginning of forward flow.

At the boundary between the forward jet and the slow backflow, viscous shearing forces develop which produce a vortex layer. Vortices are conveyed with the stream and at the same time diffuse in the manner of heat forming an enlarging wake of disturbed flow characterized by turbulent mixing. The generation of sound waves during systole in the ascending aorta does not prove that turbulence is present since vortices in the absence of turbulence can produce sound. The prominent backflow observed in this portion of the aorta in early diastole also contributes to mixing in some degree. Finally, the coronary and brachiocephalic branchings provide further dispersion as shown in the cineangiograms.

It is possible that the position of a catheter in the orifice of the aortic valve might have produced sufficient disturbance of flow to create the mixing observed in these experiments. However, no aortic incompetence was detected by changes in pressure gradient, cineangiography or by placing an additional thermistor in the outflow tract of the ventricle. In the absence of valvular incompetence the catheter should not have produced any greater disturbance of flow in the ascending than in
the descending aorta where mixing was not found. Finally, separation of flow in the ascending aorta with formation of a jet was demonstrated in the cineangiograms when the catheter was introduced into this region through the carotid artery rather than through the aortic valve orifice.

It must be emphasized that in the present experiment the flow pattern immediately adjacent to the walls was not determined by the thermistor technique. The thermistor was placed so that it measured temperature fluctuations across the aortic diameter to a distance of 1 mm from the walls. Closer approximation could have resulted in actual contact with the aortic wall with resulting failure to record blood temperature. If it were possible to measure the temperature fluctuations closer than 1 mm from the wall of the ascending aorta, a temperature gradient would have been found. Indeed, the explanation given above for the genesis of disturbed flow in the ascending aorta assumes that there is a layer of retarded flow near the walls and a stagnant region behind the valve cusps such as was visualized by cineangiography.

If the velocity of flow and the distribution of indicator were entirely equal from wall to wall and in the region distal to the valve as compared to the sinuses of Valsalva, then following sudden injection the disappearance of indicator from the ascending aorta should occur as a single slug. The fact that a significant residuum of indicator is carried over into succeeding pulse cycles, that is, that the indicator washes out of the ascending aorta in a more or less exponential fashion as shown in figure 4, indicates that the velocity of flow is not equal throughout the ascending aorta. The explanation for the observed gradual disappearance of indicator following sudden injection is that there is a relatively slow moving boundary layer close to the walls as well as a stagnant region in the sinuses of Valsalva. The prominent backflow occurring in diastole will promote the eventual mixing and dispersion of the indicator present in these areas of sluggish flow.

It does not follow that blood ejected from the ventricle will exhibit the same exponential washout from the ascending aorta. In the present experiments, using sudden injection, the cold solution was directed radially into the ascending aorta so that high concentrations were deposited in the slow moving layers near the wall. By contrast, the direction of ventricular ejection is into the well mixed, high velocity, central core of blood flow which moves rapidly out of the ascending aorta.

The question as to whether the flow in the ascending aorta is fully turbulent or simply eddying cannot be decided by the present experiments. Extensive vorticity could produce adequate mixing. According to the evidence of Coulter and Pappenheimer, turbulence occurs in blood flowing through medium bore glass tubes at a Reynolds number of approximately 1000. As pointed out by Peterson et al.11 the inlet conditions at the root of the aorta would produce further instability so that turbulence could ensue at even smaller Reynolds numbers. On the other hand, since turbulence once established does not usually revert quickly to laminar flow, it becomes necessary to explain the more streamlined pattern found in the descending thoracic aorta.

The transition from a disturbed to a more streamlined pattern of flow in the descending thoracic aorta is facilitated by several factors. The vortices are damped out by viscous forces within the fluid; flow tends to stabilize in a curved and gradually narrowing pipe such as the arch of the aorta; the flow is pulsatile, decelerating to low velocity during each cardiac cycle; and finally, the velocity of the systolic flow decreases while traversing the aortic arch particularly after the branches to the head and forelimbs are given off. A marked reduction in peak flow velocity from the ascending to the descending thoracic aorta has been recorded by Spencer et al. using the electromagnetic flowmeter.

No evidence was found in the present experiments to support McDonald's observations that the streamlines break up completely and spread across the descending aorta during peak systolic flow. With infusion of saline in this region the temperature gradient across the aortic diameter was maintained through-
out the systolic phase of the cycle and a streamlined distribution of contrast material was seen by cineangiography during peak systolic flow.

The thermistor method tends to underestimate the degree of laminar flow. The saline solution which was used had a lower viscosity than that of blood. However, the volume of injectate was small compared to the volume flow of blood so that blood viscosity probably changed very little. In one experiment, cold dog’s blood, rather than saline, was infused with no detectable difference in pattern as compared to saline in the same dog. Nevertheless, until the saline became mixed it would diffuse to some extent across the streamlines. Additional diffusion also was produced by heat transfer. Finally, the injection catheter protruding into the stream above the thermistor must have disturbed the laminar pattern to some extent. Streamlining still was demonstrated in the descending aorta during rapid forward flow despite these experimental disturbances.

Hess, in 1917, injected methylene blue solution of the same viscosity as blood, through a cannula inserted down the carotid into the arch of the aorta. He found a higher concentration of dye in the left than in the right iliac artery. Such results are compatible with the present findings since the transition to streamlined flow occurred in the distal part of the aortic arch.

Ralston and Taylor injected India ink into the left ventricle and observed streamlined filaments of ink in a glass tube inserted into a segment of the aorta. In a later study with Elliott they found different concentrations of India ink in the two renal arteries after injection into any portion of the ascending aorta above the renal arteries, including the ascending aorta. Such results would be incompatible with the presence of mixing in the aortic root and differed from the observations reported here. Using a catheter producing radially directed jet injection in the ascending aorta, Peterson et al. found practically complete mixing of the dye T-1824 with the aortic blood.

The presence of significant backflow in the ascending aorta and arch, and in the abdominal aorta below the renal arteries, agrees with observations made with various types of flow recorders. Also, in agreement with the present observations, flow velocity recordings indicated minimal backflow in the descending thoracic aorta.

Summary

A thermistor was used to record the temperature at regular intervals across the aortic diameter of dogs during the continuous infusion of cold indicator solution at various upstream locations. The results showed that the indicator mixed across the greater part of the diameter of the aorta in the ascending portion and proximal half of the arch but maintained a more streamlined pattern in the distal portion of the arch and descending thoracic aorta. These observations were confirmed by cineangiography. When two thermistors were located in different positions in the aortic root, and when cold saline was injected suddenly in their vicinity, the temperatures recorded by the two thermistors equalized immediately following the onset of systole. Sound waves also were detected during the systolic interval in the ascending but not in the descending aorta.

These findings are consistent with the presence of disturbed, but not necessarily turbulent flow in the ascending aorta; and with predominantly streamlined, but not necessarily completely laminar flow in the descending portion. The factors producing disturbed flow in the aortic root and the transition of flow to a more streamlined pattern in the descending portion are discussed in hydrodynamic terms.

It is postulated that during systole the blood ejected into the aorta separates from a slower moving boundary layer near the walls and at the edges of the valve cusps. This separation produces disturbed flow and mixing in the entering jet. While the thin layer adjacent to the walls as well as stagnant areas behind the valves do not fully mix with the central stream, they represent a relatively small proportion of the total aortic blood flow. Additional mixing is produced by the prominent backflow in early diastole and by the
branchings of the coronary and brachiocephalic arteries.

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