J. Physiol. (1954) 124, 631–639

OBSERVATIONS ON LAMINAR FLOW IN VEINS

By E. P. W. HELPS and D. A. McDONALD

From the Department of Physiology, St Bartholomew's Hospital Medical College, London

(*Received* 28 *January* 1954)

Fluid flow in pipes may be laminar or turbulent. In laminar or streamline flow the fluid particles flow in concentric laminae which vary in speed progressively from zero velocity at the wall to maximum velocity in the axial stream. A profile of these velocities forms a long parabola. With such a type of flow there is no mixing across the lumen of the tube other than that due to diffusion. Poiseuille's law only applies to laminar flow. In turbulent flow, on the other hand, the fluid particles pursue a random course so that the distribution of velocity is more nearly the same across the pipe, and there is thorough mixing of the fluid. The conditions establishing the transition from laminar to turbulent flow in pipes with steady flow were first described by Reynolds (1883), and from the use of his formula it is generally asserted that all venous flow is laminar (Burton, 1952; Green, 1944). However, the steady flow conditions of physical experiments are not found in the living body, and direct observations are needed to supplement the theoretical predictions.

Laminar flow has been seen in the veins of various experimental animals. These observations have been reviewed by Franklin (1937), who first emphasized the significance of the absence of mixing across the lumen of a vein. Since the introduction of catheterization of the great veins and the right auricle to obtain samples of venous blood the problem of mixing in the veins is of considerable practical interest. In experimental work the estimation of flow velocity from the injection of dye or radiopaque materials is dependent on the clear visualization of the parabolic profile such dyes assume in laminar flow. The presence of laminar or turbulent flow may also alter the calibration of flowmeters.

The present study reports the results of observations of laminar flow and disturbances of laminar flow in a wide range of veins, mainly in the rabbit, but also in the cat and the dog; estimates of the Reynolds' number have been made for each vein, so that it is possible to make some predictions of the nature of venous flow in larger species.

METHODS

Cinematography. Flow patterns were photographed at 16, 24 or 64 frames/sec with a Paillard-Bolex H. 16 cine-camera on Kodak Super XX-reversal 16 mm film, using a deep red filter if necessary. One series of experiments was recorded with a Kodak Cine-Special camera on Kodachrome by Mr Douglas Fisher and these have been prepared as a demonstration film (by the Wellcome Film Unit) to which reference may be made for further illustrations. Orthodox lighting systems were used.

The demonstration of laminar flow was made, wherever possible, by naturally occurring streams of relatively well-oxygenated blood showing as red streaks against the other, darker, venous blood as described by Franklin & MacLachlin (1936*a*, *b*). Otherwise Evans blue (5% in 0·9% NaCl or in 50% (w/v) dextran) was injected into a tributary of the vein being studied. This dye showed best when the venous blood was not very deoxygenated and hence fairly pink in colour. Urethane (2 g in 25% (w/v) solution/kg) was found to be the best anaesthetic in this respect and was used throughout for rabbits (pentobarbitone, 30 mg/kg, was used for cats and dogs). Animals were also given high concentrations of oxygen to breathe where it was thought that poor ventilation was causing dark venous blood. Rabbit blood saturated with carbon monoxide was used to create red streams in some cases, but the colour was not intense enough to photograph well.

Velocity of flow was measured by filming the traverse of bubbles of oxygen injected peripherally. This method has been shown to be valid for measuring arterial flow velocity (McDonald, 1952*a*). Injections of 0·1–0·2 ml. were found to be adequate for measuring flow velocity in the rabbit vena cava. Provided the injections were spaced with intervals of 2 min or more no untoward effects were noted. Venous pressure was measured with a polythene cannula in a tributary vein and a capacitance manometer (Southern Instruments Ltd.).

Operative exposure. The mesenteric and portal veins (occasionally the vena cava) were exposed through a midline abdominal incision. The abdominal vena cava was exposed retro-peritoneally through a right-flank incision, and injections were made into a femoral vein. The thoracic inferior vena cava was exposed through a lateral thoracotomy incision and injection was made from the femoral vein or a phrenic vein. The jugular vein was exposed from the front of the neck and the incision extended to the superior vena cava by a thoracotomy in the 2nd or 3rd intercostal space and by splitting the sternum. Injections were made in a marginal ear vein or a tributary in the neck. It was found possible to cannulate very small mesenteric veins by pushing a fine polythene tube (0·5 mm internal diameter) directly into them. To prevent damage by prolonged exposure, the veins, especially abdominal ones, were covered with liquid paraffin.

RESULTS

Mesentric veins. The finest branches in the mesentery were the smallest veins studied. Flow was always laminar and the streamlines were very stable. At some of the complex junctions near the root of the mesentery a stream of dye from a small vein might be seen to cross obliquely a larger vessel until it was on the far side and streams from veins proximal to it came to lie in its former position. Streams from different injection sources could be seen pursuing independent courses along the mesenteric vein.

Portal vein. Spontaneous streams of differently oxygenated blood were occasionally seen in the portal vein but usually dye had to be injected. The rate of flow varied with phases of respiration (Alexander, 1951), but respiratory movements of the liver also caused considerable lateral movements of the vein and some disturbance of flow resulted. This usually took the form of a lateral movement of the whole stream, but in some cases caused vortices to

appear. Distortion of the vein by retraction could very easily cause such vortices and for this reason moving the vein had to be avoided. Streams of dye from various sources of injection in the tributaries of the superior and inferior mesenteric veins could be seen to occupy different positions in the vein but they were not constant or predictable in any situation. Localized staining of the liver from an injection of one tributary could also be shown similar to that reported by Copher & Dick (1928) in the dog.

Abdominal vena cava. The spontaneous appearance of streams of variously coloured blood was seen in almost every experiment, especially after first opening the abdomen, although the contrast in colour is usually most marked in animals in which the circulatory rate is greatly reduced. As reported by Franklin & MacLachlin (1936*b*), they are especially well shown by the streams from the uterine veins in pregnant animals. Dye injected from the femoral vein formed easily demonstrable streams but as with the portal vein their position was not predictable. There was commonly a tendency for a stream to follow a helical course in the vena cava so that the flow from a left femoral vein, for example, might be seen to be on the right side in mid-abdomen. The pattern of flow was essentially stable in the abdominal vena cava of the rabbit even though there was a brief retrograde pulse with each respiration. When this was marked there was a tendency for the streams to be momentarily split into parallel filaments which oscillated with the changes in flow rate.

Streamlines were observed in the abdominal vena cava of the dog. The pattern of flow here was similar to that in the rabbit.

Measurements of flow velocity were made in four rabbits and two dogs. The highest velocity recorded was 18 cm/sec in a vessel of 1·0 cm diameter in a dog of 14 kg. Venous pressure at the distal end of the vena cava ranged from 5 to 12 mm Hg in different experiments.

Thoracic inferior vena cava. Spontaneous streamlines were occasionally observed in the thoracic vena cava. These were never seen to flow continuously throughout the respiratory cycle, and there was always some disturbance of flow pattern. A stream, or two parallel streams, would appear during inflation of the lungs; then during deflation an eddy would appear near the diaphragm which would obliterate the stream there. This flowed towards the heart and showed a small backward pulsation with each heart-beat. A quick succession of four or five such eddies or vortices would be formed, and analysis of the film record shows that there is a region of less disturbed flow between each one but no clear-cut stream. With inflation of the lung again the steady streams were re-established.

The demonstration of laminar flow with dye injected from the femoral vein was always unsuccessful, which suggests that the streams were broken up by disturbances in the vein. On the other hand, a small injection of dye into the phrenic vein of the rabbit could always demonstrate a distinct stream close to

the wall of the vena cava. If the dye was injected further into the lumen of the vessel its pattern would be broken up. This indicates that there is laminar flow close to the wall of the vessel, but that there is a zone of disturbed flow further in. This condition is analysed below in the Discussion, and it is enough to say here that this is probably an annular vortex disturbance due to the back pulses from the heart, and that the axial streams are likely to be relatively undisturbed. Owing to the opacity of the blood this was not verified by observation in the vein, although it has been shown in models made of glass tubes. In dogs the thickness of the vena cava wall proved too great to follow the injection of dye accurately.

Other factors causing disturbance of the blood in this vessel are the lengthening of the vena cava due to diaphragmatic movement, constriction by the diaphragm and lateral movements due to movements of the lungs. The first two of these were eliminated by making observations when the diaphragm was quiescent following hyperventilation. The effect of inflation of the lungs could only be eliminated for short periods by stopping the pump. Inflation of the left lung when the right lung was either resected or retracted to allow observation of the vein, caused the vein to be bent to the right side of the thorax. This was shown to be a partial cause of the relation of the streamline effect to inflation of the lungs described above, and it is thought that bending the vein moved the stream into the laminar boundary layer, while as the vein straightened again the stream moved into the disturbed zone. This lateral distortion of the thoracic vena cava is an artifact that presumably does not occur when the lungs are symmetrically placed in the thorax. Nevertheless, the vortices in the flow pattern described above could be seen even when the lungs were not being inflated.

The superior vena cava is not subject to so many external movements as the inferior vessel, and is also of a smaller size (especially in the rabbit which has two superior venae cavae). The disturbances of laminar pattern are much less here and dye was followed as a more or less distinct stream from the jugular or the ear vein until it entered the heart in rabbits and cats. A similar disturbance of flow to that described in the inferior vena cava might be seen here. A spontaneous stream of darker blood could sometimes be seen running from the subclavian vein, and its margin as it turned into the vena cava showed the same oscillations in time with the heart and with respiration, small vortices being formed. In spite of these vortices, mixing across the vessel was never complete and the main outlines of the tributary stream could be seen.

Pulmonary veins. Laminar flow was observed in branches of the pulmonary veins while the lungs were being inflated, but could not be visualized in vessels larger than 1–2 mm diameter in the rabbit because of their anatomical disposition.

Reynolds's number. The Reynolds number for veins of varying size are calculated from the data above. Comparable figures from Schleier (1918) in the dog and Burton-Opitz (cited by Franklin, 1937) in the cat are also included. The formula used is

$$R_e = \frac{VD\rho}{\mu}.$$

McDonald (1952*b*) and Coulter & Pappenheimer (1949), calculated this figure with radius (r) in place of diameter (D). However, as the general equation uses the 'mean hydraulic depth' (Goldstein, 1938) it is more correct to use the diameter. For comparison of the present figures with these authors, their values should, therefore, be doubled.

ρ (density) is taken as 1·054.

μ (viscosity) is taken as 0·017 poise (Green, 1944) as it is the lowest quoted in the literature and so will give the largest Reynolds numbers. (It is probable that the value 0·04 poise (Coulter & Pappenheimer, 1949) is more accurate for dogs and human beings.) No direct measurement of viscosity under existing flow conditions could be made. All observations are based on the spontaneous appearance of laminar blood streams so that the viscosity of the dye is ignored. Velocities given from personal observations are the highest recorded with presence of laminar flow in a given vessel.

Capillary (Schleier)	$D = 0{\cdot}0008$ cm	$V = 0{\cdot}05$ cm/sec	$R_e \simeq 0{\cdot}003$
Small mesenteric vein (rabbit)	$D = 0{\cdot}01$ cm	$V = 1{\cdot}0$ cm/sec	$R_e \simeq 0{\cdot}6$
Small mesenteric vein (dog, Schleier)	$D = 0{\cdot}013$ cm	$V = 0{\cdot}5$ cm/sec	$R_e \simeq 0{\cdot}4$
Portal vein (rabbit)	$D = 0{\cdot}3$ cm	V (max.) = 10 cm/sec	$R_e \simeq 190$
Abdominal vena cava (rabbit)	$D = 0{\cdot}34$ cm	V (max.) = 18 cm/sec	$R_e \simeq 360$
Thoracic i.v.c. (rabbit)	$D = 0{\cdot}6$ cm	V (max.) = 18 cm/sec	$R_e \simeq 660$
Thoracic i.v.c. (cat, Burton-Opitz)	$D = 0{\cdot}8$ cm	V (max.) = 12 cm/sec	$R_e \simeq 600$
Abdominal vena cava (dog)	$D = 1{\cdot}0$ cm	V (max.) = 15 cm/sec	$R_e \simeq 930$

Human. Thoracic venae cavae. Direct measurements of the velocity of flow are not available but may be estimated from the dimensions of the vessels and the cardiac output. The diameters quoted are a mean of measurements of five patients during thoracotomy by Mr O. S. Tubbs.

D (superior vena cava), 2·0 cm.

D (inferior vena cava), 2·0 cm.

V (mean) = 10·7 cm/sec (cardiac output 4 l./min) or 16·0 cm/sec (cardiac output 6 l./min).

$R_e = 1320$ ($V = 10{\cdot}7$) to 1980 ($V = 16{\cdot}0$) ($\mu = 0{\cdot}017$ poise).

(The actual figures should allow for a peak velocity probably double the mean velocity and a greater viscosity (e.g. 0·04 poise) for human blood compared to rabbit blood. These corrections would cancel out so that the values cited are of the right order of magnitude.)

DISCUSSION

As the velocity of flow in veins increases as they approach the heart and as the calibre is also increased, it is clear that the largest Reynolds numbers are to be found in the venae cavae. The calculations above show that the critical number of 2000 is not likely to be exceeded, under conditions of rest, in all species up to, and including, man. Flow, therefore, should be laminar if disturbing factors are not present. These factors are (i) phasic fluctuations, including backflow, due to respiration and cardiac action, (ii) distortion of vessels by external forces, and (iii) conditions of flow at junctions. Disturbances of flow reported in the observations above have been all attributed by us to factors (i) and (ii). The onset of turbulent flow is defined as the condition where small initial disturbances increase in magnitude until they involve the whole of the flowing liquid (Lamb, 1932). As the disturbances described in the flow in large veins die away again it is not accurate to call the flow turbulent at these times, even though one effect of the disturbance is to cause the same transverse mixing of blood across the vessel as is caused by turbulence. The difference in concept arises because the physical definition depends on a steady flow state and such a steady flow is not found in large veins or in arteries where the occurrence of turbulence is most in dispute. Therefore the word turbulence is avoided here.

(i) Arrest of flow with a small backflow phase was seen in superior and inferior thoracic venae cavae both in the rabbit and the dog. These observations are in keeping with the measurements of flow in the inferior vena cava of the dog by Mixter (1953) and in the superior vena cava by Brecher & Mixter (1953). A reversal of flow in a vessel under laminar condition due to an increase of pressure distally has an effect mainly on the axial and paraxial streams which will gradually cause a laminar parabola to be established in the direction of the new flow. This takes a considerable distance to establish itself (Schiller's input distance—Goldstein, 1938). Before this occurs, a region of maximum shear is set up around the paraxial laminae and a vortex ring develops. Between that and the wall of the tube a boundary layer which is still laminar continues to flow slowly in the original direction of flow. In these large veins the reversal of flow is of short duration and a steady state is never reached. The reversal is accompanied by the appearance of a vortex ring as described in the thoracic inferior vena cava. This also explains the observation that the break-up of the laminar flow does not occur with the maximum forward flow, i.e. at the maximal Reynolds number, and so differs from the typical onset of turbulence. It is also distinguished from true turbulent flow by the fact that the boundary layer nearest the wall is still laminar whereas normally turbulence commences in these layers. The transference of results in small species to a large animal such as man is, therefore, difficult as it depends on

the degree of reversal of flow, which is not accurately known, rather than on the maximal Reynolds number. It is safe to say, however, that the disturbing effect of such vortices will be greater in large vessels than in small ones.

(ii) The distortion of vessels by external forces appeared to be the main cause of the degree of disturbance seen in the portal vein and to contribute to the disturbance in the thoracic inferior vena cava. Movement of the diaphragm has been shown by X-ray cinematography to cause lengthening and narrowing of the vena cava (Franklin & Janker, 1934) in inspiration, and the reverse change appeared to occur in the portal vein in our observations. Inflation of the lungs also caused lateral distortion of the vena cava, as reported above, but without confirmatory evidence in the intact animal we cannot say that this is a normal phenomenon in vena cava or portal vein. Slight degrees of kinking of the portal vein were seen to be a potent cause of disturbed flow and may occur under normal conditions. Rapid widening of vessels with respiration is a likely cause of disturbed flow. In physical models turbulence at a R_e of 280 upwards when the entry is disturbed, is known to occur (Goldstein, 1938).

(iii) The effect of junctions on flow is largely unknown. McDonald & Potter (1951) showed that flow is still laminar at the junction of the two vertebral arteries where the Reynolds number is of the order of 100, and flow was laminar at the junction of the iliac veins of the rabbit (R_e 200–300) in the present series. However, some personal observations on glass tube models suggest that turbulence occurs at a junction at a value considerably below the normal critical one. In large species this factor may become important.

For a consideration of the validity of Poiseuille's law it is most important to know the type of flow in small vessels. The basilar artery of the rabbit (D approx. 0·1 cm, R_e 100) has stable laminar flow in spite of marked phasic fluctuations in velocity (McDonald & Potter, 1951). It is, therefore, safe to assume that all arteries smaller than this will have laminar flow. Larger arteries, however, may have transient phases of apparent turbulent flow like the rabbit aorta (D 0·3 cm, R_e 600–1000; McDonald, 1952*b*). Capillaries are commonly known to have laminar flow (see Franklin, 1937). The present observations have shown that laminar flow is certainly to be seen in veins with relatively steady conditions of flow up to a Reynolds number of 1000 (dog abdominal vena cava D 1·0 cm) so that flow may be said to be laminar in all veins outside the thorax. Within the thorax the flow is fundamentally laminar, but subject to transient disturbance in the large vessels as discussed above. These disturbances have been seen with R_e as low as 500–600, and with values of this order and higher it may be inferred that continuous laminar flow depends on steady flow conditions.

The practical importance of disturbances in laminar flow for causing mixing across a vein, mainly concerns large veins. From our observations it appears

likely that the greatest amount of mixing will occur in the thoracic inferior cava of man, but even here it may well be incomplete. In the superior vena cava it may be less and in the hepatic veins it will probably be slight and so give rise to variations in sampling where venous catheterization is used, e.g. in estimating hepatic blood flow. Such irregularities of sampling have also been noted by workers estimating cardiac output by the Fick principle, using a catheter in the right auricle or even in right ventricle or pulmonary artery. Where errors in analytic technique can be ruled out, such sampling differences must be due to persistence of streamline conditions in these vessels.

SUMMARY

1. The presence of laminar flow by direct observation has been confirmed in veins ranging from the smallest mesenteric radicles in the rabbit to the abdominal vena cava of a dog weighing 14 kg.

2. The Reynolds numbers have been computed and in the dog vena cava were of the order of 1000 at maximum. In the human the critical number of 2000 may be reached in mild exercise.

3. In the thoracic venae cavae, where marked phasic variations in flow were present, the flow pattern was more complex. With each respiration, and to a lesser extent each heart beat, an arrest, or reversal, of flow took place. This caused vortex rings to be formed, leaving a laminar boundary layer near the wall and also leaving the axial streams relatively undisturbed. These vortices caused some mixing in the vein. The effect of respiratory movements on the lumen of the vessel and the flow pattern are also discussed.

4. With regard to larger species it is concluded that when the flow reaches a Reynolds number of 500 and above the flow pattern will be easily broken by marked changes in flow rate or by external deformation of the vessel. The actual degree of such disturbance depends as much on the factors causing it as on the Reynolds number.

We are grateful to Prof. K. J. Franklin for his interest in this work and to the Wellcome Foundation for making a film of a series of the experiments. The Paillard cinecamera was financed by a grant from the Central Research Fund of London University to D.A.McD. We also thank Mr J. R. Womersley for advice on hydrodynamics and Mr O. S. Tubbs, F.R.C.S., and Mr R. Hurt, F.R.C.S., for measuring the veins of patients during operations.

REFERENCES

ALEXANDER, R. S. (1951). Influence of the diaphragm upon portal blood flow and venous return. *Amer. J. Physiol.* **167**, 738–748.

BRECHER, G. A. & MIXTER, G. (1953). Effect of respiratory movements on superior cava flow under normal and abnormal conditions. *Amer. J. Physiol.* **172**, 457–461.

BURTON, A. C. (1952). Laws of physics and flow in blood vessels. In *Visceral Circulation*, ed. Wolstenholme, G. E. W., pp. 70–84. London: Churchill.

COPHER, G. H. & DICK, B. M. (1928). 'Stream line' phenomena in the portal vein and the selective distribution of portal blood in the liver. *Arch. Surg., Chicago*, **17**, 408–419.

COULTER, N. A. jun. & PAPPENHEIMER, J. R. (1949). Development of turbulence in flowing blood. *Amer. J. Physiol.* **159**, 401–408.

FRANKLIN, K. J. (1937). *A Monograph on Veins.* Springfield, Ill.: Thomas.

FRANKLIN, K. J. & JANKER, R. (1934). Effects of respiration upon the venae cavae of certain mammals, as studied by X-ray cinematography. *J. Physiol.* **81**, 434–439.

FRANKLIN, K. J. & MACLACHLIN, A. D. (1936*a*). Stream-lines in the abdominal vena cava. *J. Physiol.* **86**, 386–387.

FRANKLIN, K. J. & MACLACHLIN, A. D. (1936*b*). Stream-lines in the abdominal vena cava in the late stages of pregnancy. *J. Physiol.* **88**, 261–262.

GOLDSTEIN, S. (ed.) (1938). *Modern Development in Fluid Dynamics*, vol. 1, pp. 279, 323. Oxford: Clarendon Press.

GREEN, H. D. (1944). Circulation: physical principles. In *Medical Physics*, ed. Glasser, O. Chicago: Year Book Publishers.

LAMB, H. (1932). *Hydrodynamics*, 6th ed., p. 663. Cambridge University Press.

MCDONALD, D. A. (1952*a*). The velocity of blood flow in the rabbit aorta studied with high-speed cinematography. *J. Physiol.* **118**, 328–339.

MCDONALD, D. A. (1952*b*). The occurrence of turbulent flow in the rabbit aorta. *J. Physiol.* **118**, 340–347.

MCDONALD, D. A. & POTTER, J. M. (1951). The distribution of blood to the brain. *J. Physiol.* **114**, 356–371.

MIXTER, G. (1953). Respiratory augmentation of inferior vena caval flow demonstrated by a low-resistance phasic flowmeter. *Amer. J. Physiol.* **172**, 446–456.

REYNOLDS, O. (1883). An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. *Phil. Trans.* **174**, 935–982.

SCHLEIER, J. (1918). Der Energieverbrauch in der Blutbahn. *Pflüg. Arch. ges. Physiol.* **173**, 172–204.