MEASUREMENT OF TURBULENT FLOW IN VASCULAR GRAFTS

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Introduction

The replacement of an occluded or diseased part of the arterial system with a prosthesis has been an established surgical procedure since the 1950's. A variety of materials, natural and synthetic, have been used with varying degrees of success; the former include autogenous vein, animal tissue, and human umbilical cord, while the latter include fabrics (in knitted and woven configurations) and expanded polytetrafluorethylene (PTFE). These devices suffer from several failure modes, primarily loss of patency due to thrombus formation and hyperplasia at the anastomoses. No single mechanism can be identified as the cause of these failures; biological and chemical interactions, fluid dynamics, and surgical technique are all known to play a role.

While much research has focused on the biological aspects, relatively little is known about the fluid dynamics of vascular grafts. Lacking measurements, some researchers have assumed the flow properties to be those of idealized vessels, e.g., cylindrical ducts with smooth, rigid walls. However, the physical appearance of some types of grafts suggest that these assumptions are invalid. For example, fabric grafts have a tubular accordion-like geometry that seems inconsistent with laminar flow; wall roughness is well documented as a major cause of turbulence in fluid dynamics.

One parameter of particular interest is the critical Reynolds number (R_c), i.e., the Reynolds number at the point of transition from laminar to turbulent flow. In general, the Reynolds number for steady tube flow is given by

$$R = Ud/\nu$$

where U is the average fluid velocity, d is the tube diameter, and ν is the kinematic viscosity of the fluid.

If the average velocity at the point of transition is U_c , then

$$R_c = U_c d / \nu$$

(1)

For a smooth-walled tube, R_c is primarily determined by the geometry of the inlet and is usually on the order of $R_c = 2000$, although it has been measured as high as $R_c = 40,000$ in some highly refined systems (1). The effect of wall irregularities, such as in a fabric graft, is to lower R_c . This paper reports the results of recent experiments to determine the extent of this effect.

Experimental Methods

A constant-head reservoir supplies continuous steady flow through a plastic tube having 6.35 mm internal diameter and 150 cm length; these dimensions ensure that the flow is fully developed (parabolic velocity profile) at the end of the tube. The length of graft under test is connected between the tube exit and the entrance to a turbine flowmeter (Flow Technology, Inc. model FTO), the latter being used to measure the volumetric flow rate. The control valve controls the flow rate and the flow discharges into an open reservoir, from which it is returned to the supply reservoir by a variable speed pump (Cole-Parmer, Inc. model 7144-04). The maximum volumetric flow rate available in this system is 32 ml/sec, corresponding to an average velocity of $U = 100$ cm/sec and a Reynolds number of $R = 6350$. For all measurements reported here, the fluid used was distilled, degassed water.

Turbulent flow is detected in this system using a hot-film anemometer probe positioned on the centerline of the flow at the downstream end of the graft. The probe (TSI, Inc. model 1264AW) is a miniature conical design having a platinum film sensing element. It is connected to an analyzer (TSI, Inc. model IFA-100) which provides a voltage output that is proportional to the fluid velocity. For laminar flow, the analyzer

output is a DC voltage; in turbulent flow, the fluid velocity fluctuates randomly and the output is a random AC signal superimposed on a DC voltage. Thus, by observing the analyzer output on an oscilloscope while increasing the flow rate, the transition point from laminar to turbulent flow may be determined. The critical Reynolds number may then be calculated from equation (1).

Fabric grafts are porous and typically have leak rates greater than 100 ml/cm²/min., so the above measurements require a means of preventing flow through the walls. This was accomplished by enclosing the graft in a sealed test chamber, consisting of a plastic cylinder of 2.5 cm internal diameter and slightly longer than the graft section under test. The chamber is sealed at the ends and at the point where the hot-film probe passes through, and is vented. When the flow is started, the graft leaks and the chamber fills. Once the chamber is full, the vent is capped and the equalized pressure prevents further flow through the walls.

Results

Prior to making any measurements with a graft in place, the point of transition from laminar to turbulent flow was determined for the plastic tube by itself, i.e., with the hot-film probe at the tube exit and the flow passing directly from the tube into the flowmeter. This was done to verify the system and technique, by comparison to the results of others for flow in a long tube, and to establish a basis of comparison for the same measurements in a graft. The measurements were then repeated with a 12 cm length of 6 mm diameter fabric graft installed as shown in Figure 1, stretched to a length of approximately 20 cm. This amount of stretching was chosen because it is representative of surgical technique at implantation (2).

The results are summarized in Table 1. Flow in the tube became intermittently unstable at R=3100 and turbulence was fully developed at R=4000. This is consistent with the results of other workers (1,3). Flow in the graft became intermittently unstable at R=1500 and was fully turbulent at R=1700. The progression from instability to full turbulence was much more rapid in the graft than in the tube, a characteristic feature of roughness-induced turbulent flow.

U(cm/s)	R	Flow Condition	
		Tube	Graft
17.7	1100	Laminar	Laminar
23.3	1500	Laminar	Unstable
25.9	1700	Laminar	Turbulent
49.2	3100	Unstable	Turbulent
63.0	4000	Turbulent	Turbulent

Table 1. Summary of flow conditions at key data points.

Conclusions

In the absence of experimental data, blood flow researchers have sometimes assumed the fluid dynamic characteristics of vascular grafts to be those of idealized vessels. This picture is misleading; the critical Reynolds number (R_c) for steady flow in a fabric vascular graft was determined to be less than one-half the value of R_c that was measured in a smooth-walled tube in the same system. Consequently, what has been assumed to be laminar flow in vivo may in fact be turbulent flow, with the associated elevated shear stress levels. Our future efforts will be directed toward quantifying the turbulence levels in fabric and other types of grafts, for pulsatile as well as steady flow.

References

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2. Curiale, Stephen V., M.D., USNMC, private communication.
3. White, F.M., Fluid Mechanics, section 6.4, McGraw-Hill, Inc., 1979

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