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Fluid Dynamics near end-to-end Anastomoses Part III in Vitro wall Shear Stress Measurement

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= **Abstract** =

The wall shear stress in the vicinity of end-to end anastomoses under steady flow conditions was measured using a flush-mounted hot-film anemometer(FMHFA) probe. The experimental measurements were in good agreement with numerical results except in flow with low Reynolds numbers. The wall shear stress increased proximal to the anastomosis in flow from the Penrose tubing(simulating an artery) to the PTFE graft. In flow from the PTFE graft to the Penrose tubing, low wall shear stress was observed distal to the anastomosis. Abnormal distributions of wall shear stress in the vicinity of the anastomosis, resulting from the compliance mismatch between the graft and the host artery, might be an important factor of ANFH formation and the graft failure. The present study suggests a correlation between regions of the low wall shear stress and the development of anastomotic neointimal fibrous hyperplasia (ANFH) in end-to-end anastomoses.

I. INTRODUCTION

The anastomotic neointimal fibrous hyperplasia (ANFH) is of common occurrence with graft implants. When it occurs, it frequently progresses to a hemodynamically flow limiting lesion and subsequent graft thrombosis. ANFH is most commonly seen around the end-to-end anastomosis region in all conduits[1-3]. Compliance mismatch has been believed to be the most probable cause of graft failure[4-6]. Those areas of compliance mismatch may have abnormal hemodynamics, particularly abnormal wall shear stress, which may induce thrombus, and in turn, lead to neointimal hyperplasia or atherosclerosis. Kim et al[7]. performed numerical simulations on flow across the end-to-end anastomosis and found that abnormal increase in the wall shear stress was observed just proximal to the anastomotic site and significant decrease in the wall shear stress was seen distal to the anastomosis.

Measurement of velocity profiles *in vivo* is a complicated task and several attempts have been made to obtain the velocity profiles in the various blood vessels both in humans and animals, Recently, point velocity and wall shear stress measurements within the arterial system have become possible with constant-temperature hot film anemometer systems. However, the wall shear stress measurement in a small compliant vessel is so difficult that it has never been performed in the region of vascular anas-

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tomosis.

FMHFA probes have been applied previously to measure the wall shear stress in physiological pulsatile flows[8-10]. Using flush-mounted hot film anemometer (FMHFA), Nandy and Tarbell [11] recently mearsured the wall shear stress in physiological fully-developed pulsatile flow situations in large rigid models of straight arteries. However, the agreement was poor during diastole because of flow reversal and diminished frequency response at low shear rates.

The aim of the present study is to measure the wall shear stress distribution across a small compliant vessel with an end-to-end anastomosis using the FMHFA probe.

Ⅱ. METHOD

1. Specimens

The Penrose tubing was used for simulating an artery, and anastomosed with 6mm standard wall PTFE graft. Specimens were sutured by Prolene 7-0with a continuous suturing technique by the same surgeon. Three different categories of anastomoses : Penrose tubing to Penrose tubing ; Penrose tubing to standard wall PTFE graft ; and standard wall PTFE graft to Penrose tubing were employed in the wall shear stress measurement studies. As shown in Figure 1, in each category the wall shear probe was located at five different positions. Each specimen was 12cm long in the upstream side from the anastomotic site in order to obtain a fully developed flow at the upstream.

2. Experiment

The hot film probe employed in this study is a miniature flush surface element(model 1268W), by TSI. Inc(ST. Paul, Minnesota), and commercially available, smallest probe. It consists of a flat end quartz rod, 1.5mm in outside diameter, and 6.3mm long. Hot film is covered with quartz coating and its sensing element is 1.0mm long and 0.125mm wide. The probe will be used in a constant temperature mode of operation as one arm of Wheatstone bridge(DISA 55M10). As shown in the Appendix, Leveque's relationship between the wall shear stress, τ_W, and the anemometer output voltage, E_B, is :

$$E_B^2 = A + B(T)\tau_W^{1/3} \quad (1)$$

Constants A, and B(T) are determined by probe calibration which was done immediately prior to each experiment.

Figure 2 shows the schematic of the experimental set-up of wall shear stress measurement. Glycerin solution was used for blood-analog fluid with absolute viscosity of 3.5cP at 37

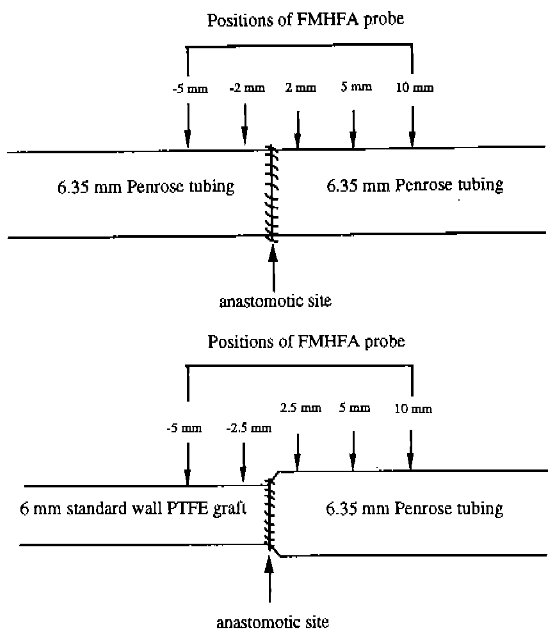


Fig. 1. Positions of FMHFA sensor on anastomosed specimens.
(a) Penrose tubing-Penrose tubing anastomosis.
(b) Penrose tubing-PTFE graft anastomosis.

℃, A constant temperature bath was used to circulate the flow in the chamber surrounding the specimen so that the specimen is maintained at a constant temperature of 37±0.5℃. A steady pump was used to circulate the fluid in the system. The straight 6.35mm I. D. Plexiglass tubing was used for a test section for calibrating the probe. The overheat ratio of 1.096 in the anemometer system was used for experiments.

A specially-designed flush-mounting device was used to mount the wall shear probe on compliant anastomosed specimens for wall shear stress measurements. The wall shear probe was mounted on the specimen at five different positions near the anastomosis. The details of the calibration and the technique to flush mount the probe on the experimental specimens are included in the work of Kim[12]. Thickness of the specimen was obtained while a small hole is made on the specimen using a punch which is attached to the end of the micrometer head. The FMHFA probe was replaced with the punch and flush-mounting was accomplished with the known specimen thickness. Mean Reynolds numbers Re($Re=\rho ud/\mu$; ρ=density, μ=absolute viscosity, u=mean inlet velocity, and d =vessel inlet diameter) varying from about 20 to 800 were employed in the present study. Wall shear stresses from the experiment were normalized by the value at 5mm proximal to the anastomotic site and compared with those of FA predictions.

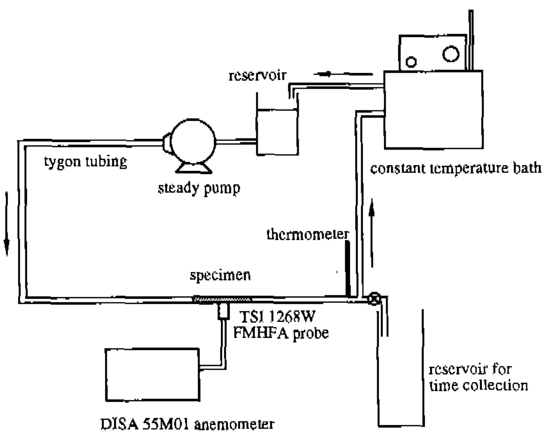


Fig. 2. Experimental set-up of wall shear stress measurement.
The specimen was replaced by the 1/4" straight Plexiglass test section for the probe calibration.

Ⅲ. RESULTS AND DISCUSSION

Figure 3(a) and 3(b) show the comparison of

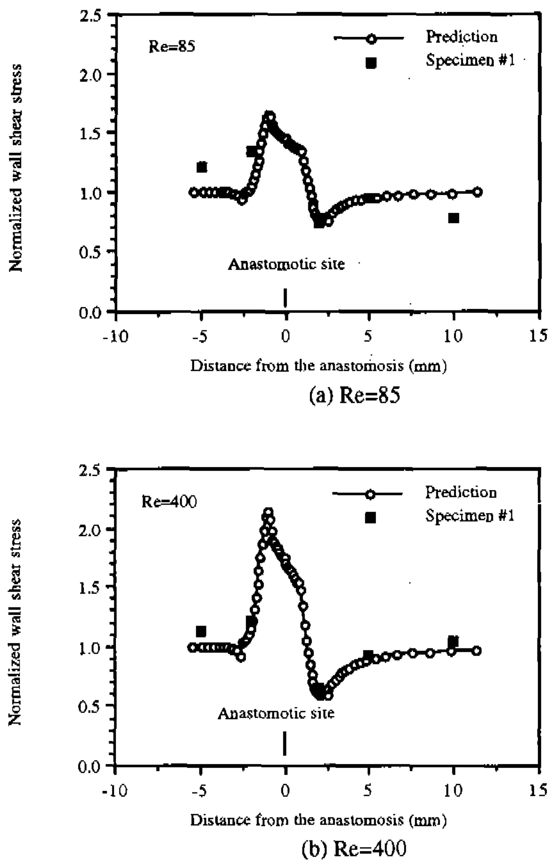
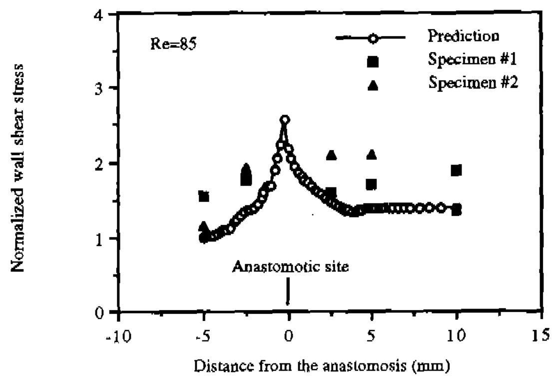


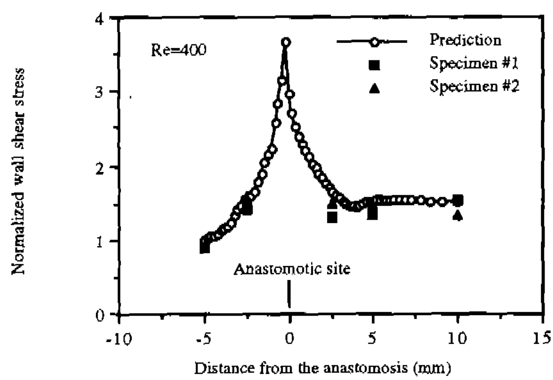
Fig. 3. Normalized wall shear stress distribution for flow through a Penrose tubing-Penrose tubing anastomosis.
(a) Re=85. (b) Re=400.

numerical and experimental normalized wall shear stress distributions for flow from the Penrose tubing to Penrose tubing at Re=85 and 400. Good agreements were observed between the experimental results and the finite analytic (FA) numerical simulations except at low Reynolds numbers. It is noted that the wall shear stress increased just proximal to the anastomotic site and then decreased distally. At 5mm proximal to the anastomosis, the magnitude of the wall shear stress was not significantly different from that in the Poisseuille flow, and the flow still remained fully developed. Similar trends were observed in the wall shear stress measurement at 2mm proximal positions. However, at 2mm distal to the anastomosis, the magnitude of the mean wall shear stress was significantly decreased. At this position, the wall shear stress at Re=400 was only about 65% of that at 5mm proximal to the anastomosis. As the Reynolds number increased, the decrease in wall shear stress in this region was observed to be more significant.

The comparison of the normalized wall shear stress as a function of the distance from the anastomosis for the flow from the Penrose tubing to the standard wall graft anastomosis(simulating proximal anstiomosis) at Re=85 and 400 are shown in Figure 4(a) and 4(b). Good agreements in wall shear stresses were also found between the experimental measurements and FA predictions in relatively high Reynolds number. In this flow through the proximal anastomosis, the increased wall shear stress was observed all along the anastomosed specimens due to the smaller inside diameter of the PTFE graft for comparable flow rates. It is noted that the wall shear stress increased just proximal to the anastomosis and then decreased just distal to the anastomosis. Normalized wall shear stresses at 2.5mm proximal to the anastomosis with Re=400 were about 50% larger than those at 5mm proximal to the anastomosis. Therefore, it can be inferred that the wall shear stress would be much larger closer to the anastomosis. As flow moves further downstream, the normalized wall shear becomes about 1.5, which is nearly constant for various Reynolds numbers. The variations in the lumen diameter at the anastomosis were more pronounced with increasing transmural pressures. In patients with hypertension, this effect might result in se-



(a) Re=85

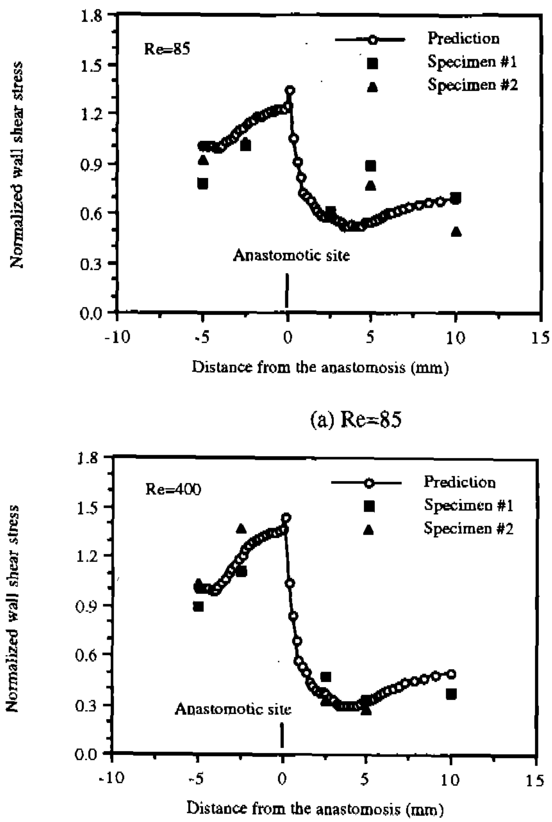


(b) Re=400

Fig. 4. Normalized wall shear stress distribution for flow through a Penrose tubing-standard wall graft anastomosis(proximal anastomosis).
(a) Re=85. (b) Re=400.

vere abnormal flow dynamics. Again, the compliance mismatch in the Penrose tubing-standard wall PTFE graft created the increased wall shear stress in the vicinity of the anastomosis.

For flow from the standard wall PTFE graft to the Penrose tubing(simulatin the distal anastomosis), the comparison of normalized wall shear stress as a function of the distance from the anastomosis at Re=85 and 400 are shown in Figure 5(a) and 5(b). As flow moved from upstream to the anastomotic site, the wall shear stress increased by about 20%. The normalized



(b) Re=400

Fig. 5. Normalized wall shear stress distribution for flow through a standard wall graft-Penrose tubing anastomosis(distal anastomosis).
(a) Re=85. (b) Re=400.

wall shear showed a remarkable decrease at the distal positions of the anastomosis. It is also of interest that the minimum value of the normalized wall shear which occurred about 5mm distally, decreased with an increase of Reynolds numbers. The low shear stress region was clearly found at the distal position of the anastomotic site. Table 1 shows the minimum value of the normalized wall shear stress for the flow from the standard wall graft to the Penrose tubing at various Reynolds numbers.

Figure 6 shows the wall shear stress plotted as a function of Reynolds number. Proximal to the anastomosis, the wall shear stress is linearly proportional to the Reynolds number. However, distal to the standard wall graft-Penrose tubing anastomosis, the experimental results and the numerical predictions showed a nonlinear characteristics between the wall shear stress and Reynolds number. Figure 7 shows velocity vectors, axial velocity profiles with normalized wall shear stress distributions for flow across proximal and distal anastomosis at Re=250 from the numerical computations. Increased wall shear stress was clearly observed proximal to the anastomosis for flow from the Penrose tubing to the vascular graft. For flow from the vascular graft to the Penrose tubing regions of low wall shear were observed distal to the anastomosis.

Wall shear stress distributions measured by the FMHFA probe agreed well with FA predictions except for flow at the low Reynolds numbers. The main reason for this is the instability of the FMHFA probe in low Reynolds numbers. Eq(1) is the basic operating equation which has been employed to measure the wall shear stress in the literature. Several investigators have considered the errors associated with the use of

표1. 여러 관강내 압력에서의 펜로스관, 펜로스관 문합 주위의 최대, 최소 벽전단응력

Table 1. The maximum and minimum wall shear stress of Penrose tubing-Penrose tubing anastomosis at various transmural pressures.

unit＝Pa

Re	upstream condition	13.3 KPa (100mmHg) max.	13.3 KPa (100mmHg) min.	20.0 KPa (150mmHg) max.	20.0 KPa (150mmHg) min.	26.7 KPa (200mmHg) max.	26.7 KPa (200mmHg) min.	33.3 KPa (250 mmHg) max.	33.3 KPa (250 mmHg) min.
250	parabolic	0.68 (-0.9)	0.37 (2.0)	1.09 (-0.9)	0.18 (2.1)	1.38 (-1.1)	0.11 (2.0)	1.40 (-0.3)	0.10 (1.4)
	uniform	3.18 (-1.0)	0.70 (2.1)	3.87 (-1.0)	0.28 (2.1)	5.03 (-1.1)	0.08 (2.1)	4.87 (-0.3)	-0.02 (1.4)
400	parabolic	1.60 (-1.0)	0.44 (2.1)	1.97 (-1.0)	0.22 (2.1)	2.51 (-1.1)	0.11 (2.1)	2.46 (-0.3)	0.07 (1.4)
	uniform	6.26 (-1.0)	0.77 (2.1)	7.78 (-1.0)	0.21 (2.1)	10.31 (-1.1)	-0.15 (2.1)	9.93 (-0.3)	-0.34 (1.4)

Note : The numbers in parenthesis specify the distance from the anastomosis(㎜)

표 2. 여러 관강내 압력에서의 테프론 인공혈관문합 주위의 최대, 최소 벽전단응력

Table 2. The maximum and minimum wall shear stress in the vicinity of Penrose tubing-PTFE vascular graft anastomosis at various transmural pressures

unit＝Pa

Re 250	upstream condition	13.3 KPa (100mmHg) max.	13.3 KPa (100mmHg) min.	20.0 KPa (150mmHg) max.	20.0 KPa (150mmHg) min.	26.7 KPa (200mmHg) max.	26.7 KPa (200mmHg) min.	33.3 KPa (250 mmHg) max.	33.3 KPa (250 mmHg) min.
Flow from Penrose tubing to standard wall graft	parabolic	1.65 (-0.2)	0.72 (3.9)	1.69 (-0.2)	0.76 (4.1)	2.11 (-0.2)	0.80 (3.9)	2.33 (-0.2)	0.82 (3.8)
	uniform	4.74 (-0.2)	1.71 (3.9)	4.76 (-0.2)	1.79 (4.1)	6.04 (-0.2)	1.89 (3.9)	6.65 (-0.2)	1.89 (3.7)
Flow from Penrose tubing to thin wall graft	parabolic	0.78 (-0.8)	0.55 (4.0)	1.20 (-0.4)	0.62 (4.0)	1.60 (-0.4)	0.68 (4.0)	1.94 (-0.4)	0.71 (4.1)
	uniform	2.14 (-0.8)	1.34 (4.0)	3.46 (-0.4)	1.51 (4.0)	4.76 (-0.4)	1.66 (4.0)	5.87 (-0.4)	1.71 (4.1)
Flow from standard wall graft to penrose tubing	parabolic	0.81 (0.2)	0.21 (4.2)	0.53 (0.2)	0.14 (5.8)	0.82 (0.2)	0.07 (6.2)	0.84 (0.2)	0.02 (6.0)
	uniform	2.13 (0.2)	0.39 (4.2)	2.05 (0.2)	0.21 (5.7)	2.13 (0.2)	0.06 (6.2)	2.21 (0.2)	-0.06 (5.8)
Flow from thin wall graft to Penrose tubing	parabolic	0.71 (0.2)	0.20 (3.7)	0.72 (0.0)	0.21 (3.2)	0.76 (0.0)	0.11 (3.4)	0.80 (0.0)	0.02 (3.8)
	uniform	1.96 (0.2)	0.36 (3.7)	1.92 (0.0)	0.41 (3.2)	2.05 (0.0)	0.14 (3.4)	2.17 (0.0)	-0.06 (3.6)

Note : The numbers in parenthesis specify the distance from the anastomosis(㎜)

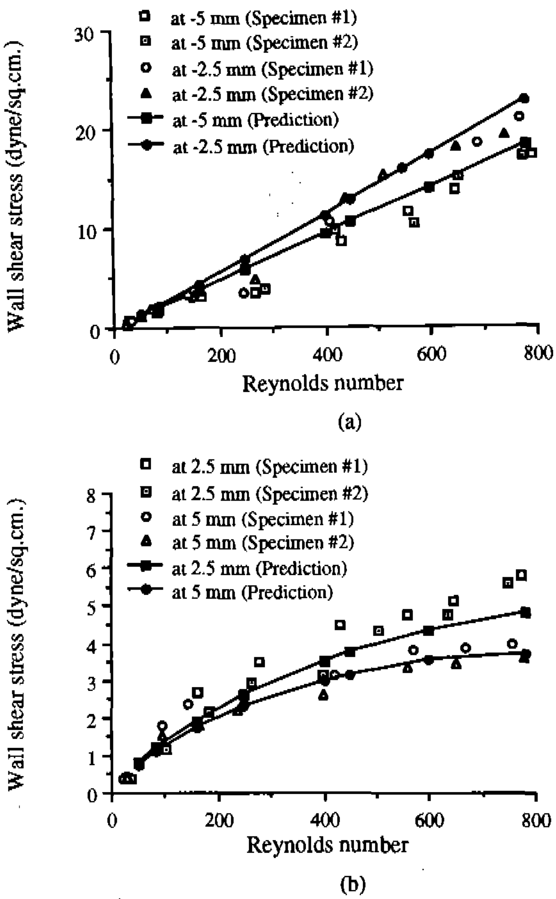


Fig. 6. Wall shear stress as a function of Reynolds number for flow through distal anastomoses.
(a) Proximal positions. (b) Distal positions.

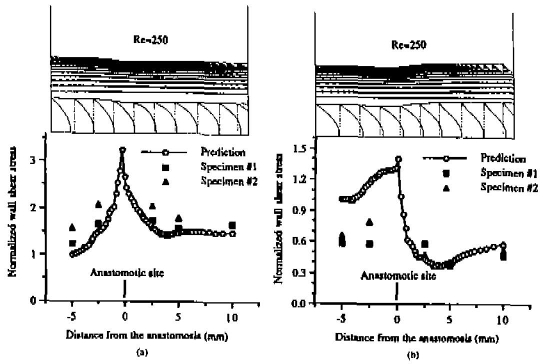


Fig. 7. Velocity vectors, axial velocity profiles and wall shear stress distributions.
(a) Near a proximal anastomosis.
(b) Near a distal anastomosis.

Leveque theory to model mass and heat transfer probes near a stagnation point where the parallel flow assumption breaks down[13, 14]. Its validity requires that the thermal boundary layer thickness be smaller than the viscous boundary layer thickness, i. e. $\delta_T<\delta_V$. It is also necessary that the time constant for thermal diffusion over the probe length be small compared to the smallest one in the time dependent shear field, so that the probe is quasi-steady, and that the Peclet number Pe(Pe=RePr, Pr=$\mu c_P/k$, c_P=specific heat, and k=thermal conductivity) be sufficiently large for the axial diffusion to be neglected. Pedley [14] indicated that Pe has to be greater that 400 for accuracy to be within 2%. The Peclet number is low for the FMHFA study and the validity of negligible axial diffusion is questionable. However, Pedley [14] indicated from the detailed analysis of the axial diffusion term that the Leveque theory is in error by 12% at Pe=10.5% at Pe=100, and 2% at Pe=400. Hanratty [13] concluded that the error associated with non-parallel flow is negligible at distances greater than 5film diameters from the stagnation point, since the diameter of the hot film was only 0.125mm for the present study. Thus, such errors are intolerable.

In summary, for flow from the Penrose tubing to PTFE vascular grafts simulating the upstream junction, increased wall shear stress was observed in both experimental and numerical results. On the other hand, for from the Penrose tubing to PTFE grafts, simulating the downstream anastomosis, decreased wall shear stress was observed distal to the anastomosis, The nonlinear characteristics of the wall shear stress with respect to the Reynolds number is noted at the distal position of the anastomosis in this type of flow. It suggests that the increased flow rate may not provide a wash-out of the fluid in this low shear stress region. Due to the limitations of the probe size, the wall shear stress very close to the anastomotic site could not be obtained. However, the wall shear measurements using the FMHFA probe provided a good enough picture of the wall shear stress distribution in the vicinity of the end-to-end anastomosis.

Ⅳ. CONCLUSIONS

The wall shear stress of the flow across end-to-end anastomoses was measured using the FMHFA probe and compared with the numerical results. The experimental results were in good agreement with the numerical results. From the present study, the following conclusions can be drawn :

1. In flow from the Penrose tubing to PTFE grafts, simulating a proximal or upstream anastomosis, the maximum wall shear stress was measured just proximal to the anastomosis.
2. In flow from the vascular graft to the Penrose tubing, simulating the distal ar downstream anastomosis, the minimum wall shear stress was measured distal to the anastomosis.
3. Discrepancies in the wall shear stress for low Reynolds number was found. The experimental results overestimated the wall shear stress for the flow with low Reynolds number.
4. The magnitudes of wall shear stress were significantly lower distal to the anastomosis site in flow from the prosthetic graft to the Penrose tubing. The regions of low wall shear stress were located closer to the anastomosis with thin wall PTFE graft than that with standard wall PTFE graft.
5. The wall shear stress acting downstream of the distal anastomosis behaves nonlinearly with the Reynolds number.
6. There is a good correlation of the region of low shear stress and the preferential sites of the ANFH formation.

The present study clearly revealed that the compliance mismatch across the anastomosis is the main factor in abnormal fluid dynamics. Mismatch of instantaneous diameters due to the compliance mismatch between the graft and the host artery resulted in the abnormal wall shear stress distibution near the anastomotic region. By matching compliances of synthetic grafts with those of host arteries as closely as possible, the flow-induced shear stress on platelets and endothelial cells, anastomotic stress and energy dissipation will be reduced.

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APPENDIX. THEORY BEHIND THE FMHFA PROBE

Figure A. 1 shows viscous and thermal boundary layers on the FMHFA probe.

Assuming that the thermal boundary layer thickness, δ_T, is much smaller than the viscous boundary laber thickness, δ_V, with negligible axial diffusion and velocity in y-direction, the well known Leveque solution is :

$$T=\frac{T_a}{\Gamma(4/3)}\int_0^{\eta}\exp(-\eta^3) \qquad \text{(A-1)}$$

where $\eta=y(\frac{S}{9}kx)^{1/3}$ (A-2)

k is the thermal conductivity of the medium, and S is the wall shear rate.

The averag heat flux, q, is obtained as :

$$q=\frac{1}{L}\int_0^L k(\frac{\partial T}{\partial y})_{y=0}\,dx \qquad \text{(A-3)}$$

where L is the length of the film in the direction of flow.

The following expression can be written for heat transfer coefficient h :

$$\frac{hL}{k}=0.807(\frac{SL^2}{k})^{1/3} \qquad \text{(A-4)}$$

where

$$h=\frac{q}{(T_w-T_a)} \qquad \text{(A-5)}$$

Thus,

$$q=0.807L^{-1/3}k^{2/3}s^{1/3}(T_w-T_a) \qquad \text{(A-6)}$$

Assuming that the electrical power P fed into the heated element is converted completely into thermal energy Q^1, we will have

$$Q_1=aq=P=\frac{E_B^2}{R_W} \qquad \text{(A-7)}$$

where a is area of the film, E_B is the anemometer bridge voltage, and R_W is the resistance of the film,

Thus,

$$E_B^2=0.807aR_WL^{-1/3}k^{2/3}(T_w-T_a)S^{1/3} \qquad \text{(A-8)}$$

or

$$E_B^2 = B_1(T)S^{1/3} \qquad (A\text{-}9)$$

and

$$B_1(T) = 0.807\ a\ R_W(T_w - T_a)L^{-1/3}K^{2/3} \qquad (A\text{-}10)$$

If the heat conduction from the element to the surrounding subtrate material is taken into consideration, the following equation is well correlated by this form :

$$E_B^2 = A_1 + B_1(T)S^{1/3} \qquad (A\text{-}11)$$

or

$$E_B^2 = A_2 + B_2(T)\tau_w^{1/3} \qquad (A\text{-}12)$$

Canstants A_1, A_2, $B_1(T)$ and $B_2(T)$ are determined by calibration. The terms A_1 and A_2 represent heat losses to the subtrate. They give an effective length of heat transfer surface many times larger than the length of the film L. The terms $B_1(T)$ and $B_2(T)$ are, in general, smaller in liquids than air.

Since the wall shear stress τ_w is known either from theory or measurements, fully-developed pipe flow is widely used for the laminar calibration of wall shear probes.