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# The Wall Shear Rate Distribution Near an End-to-End Anastomosis : Effects of Graft Compliance and Size

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## Abstract

The patency rates of small diameter vascular grafts are disappointing because of the formation of thrombus and intimal hyperplasia. Among the various factors influencing the success of graft surgery, the compliance and the size of a graft are believed to be the most important physical properties of a vascular graft. Mismatch of compliance and size between an artery and a graft alters anastomotic flow characteristics, which may affect the formation of intimal hyperplasia. Among the hemodynamic factors influencing the development of intimal hyperplasia, the wall shear stress is suspected as the most important one. The wall shear stress distributions are experimentally measured near the end-to-end anastomosis models in order to clarify the effects of compliance and diameter mismatch on the hemodynamics near the anastomosis. The effects of radial wall motion, diameter mismatch and impedance phase angle on the wall shear rate distributions near the anastomosis are considered. Compliance mismatch generates both different radial wall motion and instantaneous diameter mismatch between the arterial portion and the graft portion during a flow cycle. Mismatch in diameter seems to be affecting the wall shear rate distribution more significantly compared to radial wall motion. The impedance phase angle also affects the wall shear rate distribution.

Key words: Vascular Graft, Shear Stress, Intimal Hyperplasia, Compliance, Size

## Introduction:

Vascular grafts have been used in order to maintain blood circulation when the lumen of an artery is blocked by the atherosclerotic plaques or a portion of a blood vessel is lost due to an accident. Vascular grafts can be anastomosed with an artery in end-to-end, end-to-side or side-to-side fashion. The patency rate of a small size vascular graft is poor due to the development of intimal hyperplasia and the formation of thrombus following the surgery. Biocompatibility and surface characteristics of the graft material, the compliance and the size of a graft, suture techniques and hemodynamics are believed to be important factors influencing the success of graft surgery. Hemodynamics may play an important role in the development of intimal hyperplasia and thrombus formation, and it is affected by the physical properties of a graft such as the diameter and the compliance of a graft. The wall shear rate[1,2], wall shear stress[3,4], flow separation and recirculation[5], and turbulence[6] are suspected as major fluid dynamic factors influencing the development of intimal hyperplasia. Among these, the wall shear stress has been known to be the most important factor. Therefore, we would like to clarify the wall shear rate changes near the end-to-end anastomosis due to the mismatch of the physical properties of an artery and a vascular graft.

The mechanism by which grafts tend to fail varies depending on the length of time from graft insertion. Early graft failures are due to technical failures during the surgery. Late graft failure is attributable to the anastomotic intimal hyperplasia, which is characterized by abnormal thickening of the inner layer of an arterial wall. In the early stage

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of graft healing, a blood clot will form at the graft surface. The clot is initially formed of platelets. Complex coagulation cascade is activated, and a pseudointimal layer is formed. The pseudointimal layer is devoid of cellular elements such as endothelial cells and smooth muscle cells, and is mainly composed of platelets, fibrins, and trapped red blood cells. During the process of pseudointimal hyperplasia, the thrombogenicity of a graft surface is particularly important, and the relevant fluid dynamic characteristics are flow separation, recirculation, particle resident time and wall shear stress. A flow recirculation zone is observed near the sudden tubular expansion, which occurs due to mismatch of the size and the compliance between a host artery and a vascular graft. Flow velocities are decreased and pressure is increased as the lumen size is increased. Adverse pressure gradient pushes the fluid near the wall backward, and boundary layer separation occurs. When the boundary layer is separated, sluggish vortex motion forms flow recirculation. The aggregation and wall adhesion of platelets are enhanced in these disturbed flow regions. Platelets trapped in a recirculation zone increase the particle resident time, and the convection of platelets to the wall is enhanced near the reattachment point[7,8]. The wall shear stress also affects the platelet aggregation[9]. Low wall shear rates in the disturbed flow region promote platelet adhesion to an arterial wall and pseudointimal development. High shear stress does not prevent the aggregation or adhesion of platelets to the graft surfaces, but it does decrease the size of platelet aggregates[10]. But shear stress higher than normal (e.g. 70 dyne/㎠) causes an exponential increase in thrombus area because of platelet activation by the shear stress[11].

In the process of developing neointimal hyperplasia, smooth muscle cells migrate from the host artery into the graft after the initial phase of platelet covering[12]. Various factors - such as platelet derived growth factor, growth factor stimulating smooth muscle cell migration and proliferation, leukocyte recruitment and wall adhesion, and the shear stress induced by fluid motion - have been proposed in order to elucidate the etiology of intimal hyperplasia[13]. Among these factors, hemodynamic shear stress is strongly affected by the physical properties of a vascular graft. Mismatch of the compliance and the size between a host artery and a graft generates flow field changes near the anastomosis, and the shear stress distributions are altered by the insertion of the compliance and size mismatched graft.

Many studies have shown that intimal thickness is correlated to a low mean shear stress[12,14.] Oscillatory shear stress may provide a favourable hemodynamic environment for intimal thickening. In order to quantify the oscillatory shear stress, the oscillatory shear index (OSI) is defined by the time integration of the wall shear stress acting in the direction opposite to the mean flow divided by the time integration of the absolute value of wall shear stress over a period. Ku et al.[15] showed the positive correlation between OSI and intimal thickness in a carotid artery bifurcation. But the correlation between OSI and intimal hyperplasia was poor on the distal bed in end-to-side anastomosis. Also, temporal and spatial variations of shear stress are considered to be the hemodynamic factors affecting the formation of intimal hyperplasia. Low temporal variations of shear stress have been shown to be associated with vein graft failure4 and intimal thickening at the artery wall[15]. The regions of high spatial and/or temporal shear gradients are suspected to be correlated with intimal hyperplasia on the host artery bed in end-to-side anastomoses[16,17].

Even though the effects of the wall shear stress on the intimal hyperplasia are still controversial and the mechanism of intimal hyperplasia development influenced by the wall shear stress is unclear, many people still believe that the wall shear stress is the most important hemodynamic factor affecting the success of graft surgery. Therefore, the changes of wall shear stress distribution near the anastomosis affected by compliance and size of a vascular graft are studied in this study.

## MATERIALS AND METHODS

Flow visualization using a photochromic dye has been used in order to measure the wall shear strain rate[18-20]. A photochromic dye shows photochromic behavior by changing its color by the excitation of the light of an appropriate wavelength. The dye becomes colorless again within a few seconds after the removal of the stimulating light by the reverse photochromic reaction. The photochromic dye employed is TNSB (1',3',3'-trimethyl-6-nitroindoline-6-spiro-2-benzospyran) which can be excited by the ultraviolet light wave. A very small amount of TNSB is dissolved in a non-polar solvent. The transparent working fluid is excited by a pulsed nitrogen laser, and a dark blue tracer line is generated along the path of a laser beam. Within a few milliseconds after laser triggering, the movement of the tracer line is pictured by a camera. The velocity profile is calculated by dividing the displacement profile by the time interval between laser triggering and picture taking. The wall shear rate is calculated from the velocity gradient at the wall. This technique has been successfully used in wall shear rate measurement.

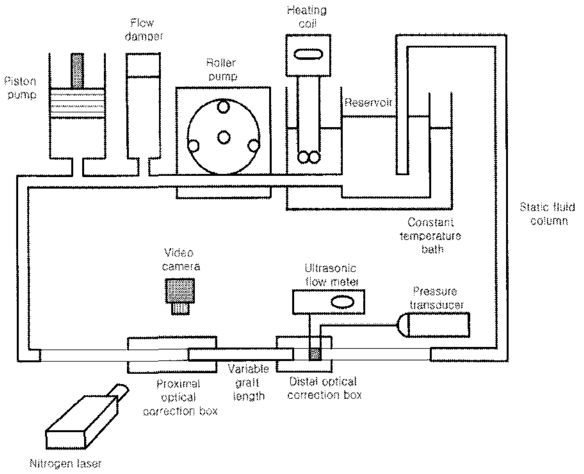

Figure 1 Schematic diagram of experimental apparatus.

In order to clarify the effects of compliance mismatch on the wall shear rate distributions, an end-to-end anastomosis model was made of elastic silicone rubber (Sylgard 184, Dow Corning Co.). The arterial portion of the model had a wall thickness in the range of 0.4-0.5 mm while the graft portion had a wall thickness ten times greater than the arterial section. The elastic arterial portion of a model showed 4-6% diameter changes over a 50 mmHg pressure variation. The compliance of this model (0.08-0.12%/mmHg) is the typical value of a medium size artery. The compliance of the graft portion of the model was about ten times less than the arterial portion, and the diameter variation was negligible over 50 mmHg pressure variation. The inside diameter of the model was 8 mm (both arterial and graft portions), and the graft portion was about 20 diameters long. This model was stretched a little bit when it was inserted into a flow loop. The inside diameters of the elastic artery and the rigid graft portion were identical at zero transmural pressure and the compliance of the graft portion was ten times less than that of the arterial portion. When this model was inserted into a flow loop, the diameter of the elastic arterial portion was increased at the mean pressure (104 mmHg) and slight diameter mismatching (about 6%) was produced. The flow loop, which consisted of a roller pump, piston pump, flow damper, test section and reservoir, generated sinusoidal flow waveform (Figure 1). The impedance phase angle ($\phi$) was varied by controlling the wave reflection. Wave reflection was altered by changing the amounts of clamping and the locations of the clamping site. The unsteadiness parameter was 3.9, and the mean and peak Reynolds numbers were 150 and 290 (for a phase angle of -56 degrees) and 180 and 320 (for a phase angle of -16 degrees), respectively. The photochromic flow visualization method was used to measure the wall shear rates near the proximal and distal anastomosis regions.

## RESULTS

### The effects of compliance mismatch

Time averaged means of the measured wall shear rate ( $\gamma_m$) are normalized by the wall shear rate at the proximal straight tube under steady Poiseuille flow at the mean flow rate ( $\gamma_p$). The distributions of normalized wall shear rate are shown in Figure 2. The wall shear rates under steady flow ( $\gamma_s$) at different axial locations are also normalized by $\gamma_p$, and shown in Figure 2. The steady shear rate

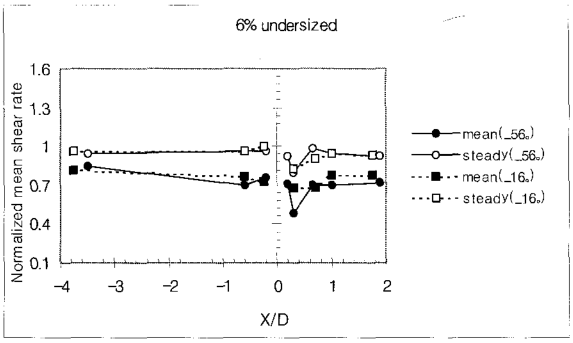

Figure 2 Normalized mean and steady wall shear rate.
Distribution is near the anastomosis in the 6% undersized model. The mean and steady shear rates are normalized by the wall shear rate predicted by Poiseuille law. X/D denotes the dimensionless axial location. X is the distance from the anastomotic site - negative values are for the proximal sites and the positive values are for the distal sites, and D is tube diameter (data from Rhee and Tarbell[19]).

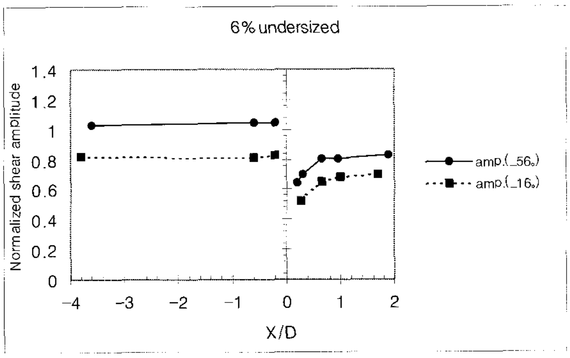

Figure 3 Normalized wall shear rate amplitude.
Distribution is near the anastomosis in the 6% undersized model. The shear rate amplitudes are normalized by the wall shear rate amplitude based on the Womersley's rigid tube theory. X/D denotes the dimensionless axial location. X is the distance from the anastomotic site - negative values are for the proximal sites and the positive values are for the distal sites, and D is tube diameter (data from Rhee and Tarbell[19]).

increases near the proximal anastomosis and decreases near the distal anastomosis. The axial variations of steady wall shear rate are due to the converging and diverging geometry caused by slight mismatch of diameters - the graft is 6% undersized. The mean shear rate near the distal anastomosis is up to 40% lower than that at the proximal straight portion. The axial distribution of mean wall shear rate is similar to that of steady wall shear rate in shape, but the normalized mean shear rates are consistently lower (10-30%) than the normalized steady shear rate. The difference between the normalized mean shear rate and the normalized steady wall shear rate shows the effects of radial wall motion. The mean shear rate distribution is not affected significantly by the impedance phase angle. The amplitudes of shear rate waveform under sinusoidal flow are normalized by the wall shear rate amplitude based on Womersley's rigid tube theory ( $\gamma_{ampw}$)[21] (Figure 3). The amplitudes of wall shear rates are lower by 20% at -16° phase angle compared to those at -56°, and they seem to be affected by the impedance phase angle. Mismatch of compliance between a host artery and a vascular graft changes the wall shear rates via two different pathways. Since the differences in compliance generate different radial wall motion in the arterial and graft portion, different radial wall movement causes the changes in flow pattern. Another factor affecting the wall shear rate distribution is the converging and diverging geometry near the anastomosis caused by the different radial distention. Even though the diameters are well matched at the mean pressure, the diameter changes differently during a flow cycle and instantaneous diameter mismatches are observed.

### The effects of compliance and diameter mismatch

The differences between the mean wall shear rate and the steady wall shear rate show the effects of radial wall motion while the differences in mean shear rate between at the proximal straight portion and at the anatomotic regions shows the effects of diameter mismatch. These two differences are similar in magnitude in the well-matched end-to-end graft model (6% undersized graft), therefore, it is hard to point out which one (either radial wall motion or diameter mismatch) is more significantly affecting the shear rate changes. In order to elucidate the effects of diameter mismatch on the wall shear rate istribution, end-to-end anastomosis models with a 16% undersized graft and a 13% oversized graft were constructed. The compliance of arterial section was 0.07-0.11% per mmHg, and the graft portion was rigid. The models were inserted into a flow loop, and a sinusoidal

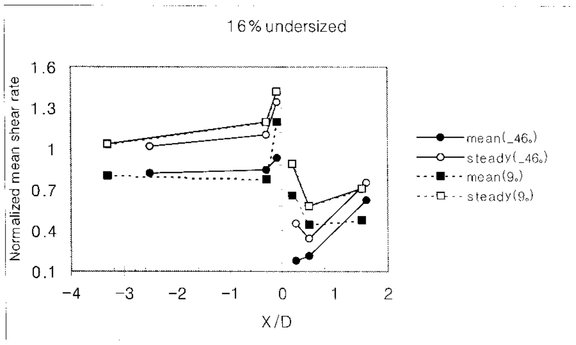

Figure 4 Normalized mean and steady wall shear rate. Distribution is near the anastomosis in the 16% undersized model. X/D denotes the dimensionless axial location. The mean and steady shear rates are normalized by the wall shear rate predicted by Poiseuille law. X is the distance from the anastomotic site - negative values are for the proximal sites and the positive values are for the distal sites, and D is tube diameter (data from Weston *et al.*[20]).

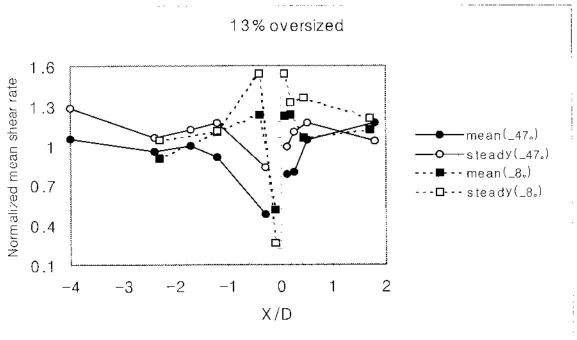

Figure 5 Normalized mean and steady wall shear rate. Distribution is near the anastomosis in the 13% oversized model. The mean and steady shear rates are normalized by the wall shear rate predicted by Poiseuille law. X/D denotes the dimensionless axial location. X is the distance from the anastomotic site - negative values are for the proximal sites and the positive values are for the distal sites, and D is tube diameter (data from Weston *et al.*[20]).

flow wave was generated. The flow characteristics are determined by the Reynolds number and the unsteadiness parameter, which is defined as the ratio of oscillatory inertial force and viscous force ( $\alpha= r\sqrt{\omega/\upsilon}$, r: tube radius, ω:angular velocity, υ:kinematic viscosity). The unsteadiness parameter was 3.6, and the mean and peak Reynolds numbers were 170 and 290 (for a phase angle of -46 degrees) and 160 and 350 (for a phase angle of 9 degrees) in the model with a 16% undersized graft. The unsteadiness parameter was 3.8, and the mean and peak Reynolds number were 220 and 400 (for a phase angle of -47 degrees) and 220 and 370 (for a phase angle of -8 degrees) in the model with a 13% oversized graft. The photochromic flow visualization method was used to measure the wall shear rates near the proximal and distal anastomotic regions.

The mean shear rate and steady shear rate are normalized by the wall shear rate predicted by Poiseuille law ( $\gamma_p$). The normalized mean shear rates are lower (10-40% in 16% undersized graft, and 10-30% in 13% oversized graft) than the normalized steady shear rate at most locations (Figures 4 and 5). The normalized mean wall shear rate increases up to 16% (ϕ=-46°) and 50% (ϕ=9°) near the proximal anastomosis and decreases down to 80% (ϕ=-46°) and 50% (ϕ=9°) near the distal anastomosis in a 16% undersized model. The normalized mean wall shear rate decreases down to 50% (ϕ=-47° and ϕ=-8°) near the proximal anastomosis and increases up to 10% (ϕ=-47°) and 20% (ϕ=-8°) near the distal anastomosis in a 13% oversized model The amplitudes of the shear rate waveform under a sinusoidal flow are normalized by the wall shear rate amplitude based on Womersley's rigid tube theory ( $\gamma_{ampw}$) and the normalized wall shear rate amplitude distributions are shown in Figures 6 and 7. The shear rate amplitude is higher (up to 40%) or lower (down to 60%) than $\gamma_{ampw}$ depending on the measurement locations and the models. The phase angle affects the shear rate amplitude distributions significantly.

## DISCUSSION

The failure of a medium to small size graft is caused by anastomotic intimal hyperplasia and thrombus formation. Biocompatibility of the graft material, suture technique, porosity, compliance and size are suspected as important parameters affecting the success of graft surgery. Among these factors, the compliance and size of a graft are important physical parameters, and mismatch of compliance and size between an artery and a graft have been shown to be the important factors and size between an artery and a graft causes wave reflection, abnormal arterial wall stress and flow disturbances. In this paper, we concentrate on

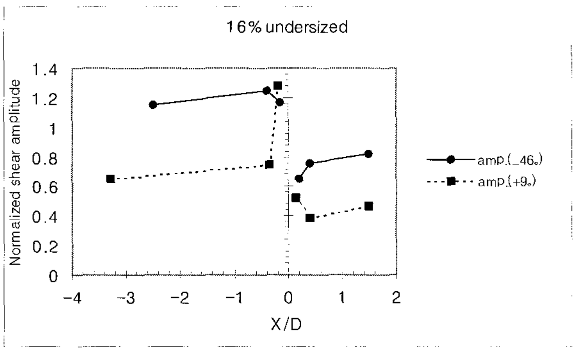

Figure 6 Normalized wall shear rate amplitude.

Distribution is near the anastomosis in the 16% undersized model. The shear rate amplitudes are normalized by the wall shear rate amplitude based on the Womersley's rigid tube theory. X/D denotes the dimensionless axial location. X is the distance from the anastomotic site - negative values are for the proximal sites and the positive values are for the distal sites, and D is tube diameter (data from Weston *et al.*[20]).

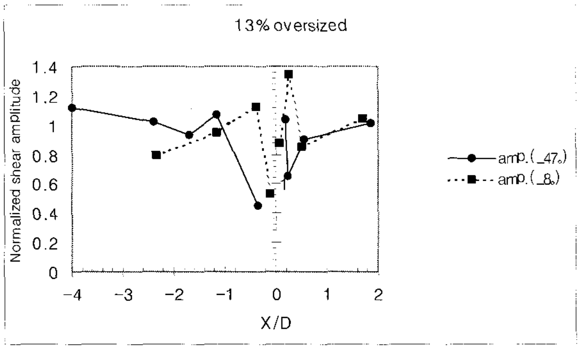

Figure 7 Normalized wall shear rate amplitude.

Distribution is near the anastomosis in the 13% oversized model. The shear rate amplitudes are normalized by the wall shear rate amplitude based on the Womersley's rigid tube theory. X/D denotes the dimensionless axial location. X is the distance from the anastomotic site - negative values are for the proximal sites and the positive values are for the distal sites, and D is tube diameter (data from Weston *et al.*[20]).

the flow field changes caused by the compliance and size mismatch in an end-to-end anastomosis of an artery and a vascular graft. Among the various hemodynamic factors affecting the development of para-anastomotic intimal hyperplasia, wall shear stress has been looked upon as the important one because many researchers have shown the correlations between intimal thickening and low and oscillatory shear stress[12,14,15] or the temporal and spatial gradient of wall shear stress[16,17]. Wall shear rate distributions are measured near the end-to-end anastomosis of an elastic artery and a rigid graft under a sinusoidal flow waveform. Three different sizes of graft are tested - size-matched graft (6% undersized at mean pressure), small graft (16% undersized at mean pressure), and large graft (13% oversized at mean pressure). The mean wall shear rates are reduced by radial wall motion by 10% to 40% in all models. The mean wall shear rates are also changed along the axial location of the model due to the converging/ diverging geometry caused by diameter and compliance mismatch. The mean wall shear rates increase up to 50% near the proximal anastomosis and decrease down to 80% near the distal anastomosis in the 16% undersized graft. In the 13% oversized graft, the mean wall shear rates decrease down to 50% near the proximal anastomosis and increase up to 20%. Relatively small mismatch in diameter (13% oversized or 16% undersized) causes the mean wall shear rate variation along the axial positions of the model in the range of 100% of the proximal mean shear rate, which are significantly higher than the shear rate changes caused by radial wall motion. The steady wall shear rate increases up to 200% near the proximal anastomosis and decreases down to 100% in 18% undersized graft[19]. Therefore, mismatch in diameter seems to be affecting the wall shear rate distribution more significantly compared to radial wall motion. The impedance phase angle has small effects on the mean wall shear rates in the 6% undersized graft, but it has pronounced effects on the mean and the amplitude of the wall shear rate in the diameter mismatched grafts. Compliance mismatch generates both different radial wall motion and instantaneous diameter mismatch between the arterial portion and the graft portion during a flow cycle. These two effects are combined, and it is hard to segregate them. But the reduced wall shear rates in the disturbed flow region, either by radial wall motion or by diverging geometry, should be avoided because they provide a favorable hemodynamic environment for the development of intimal hyperplasia.

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