순환기질환의공학회
2002년도 춘계학술강연회

분지혈관내 혈액유동의 특성해석

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장소 : 숭실대학교

한 국 항 공 대 학 교
항공우주 및 기계공학부
교 수 유 상 신

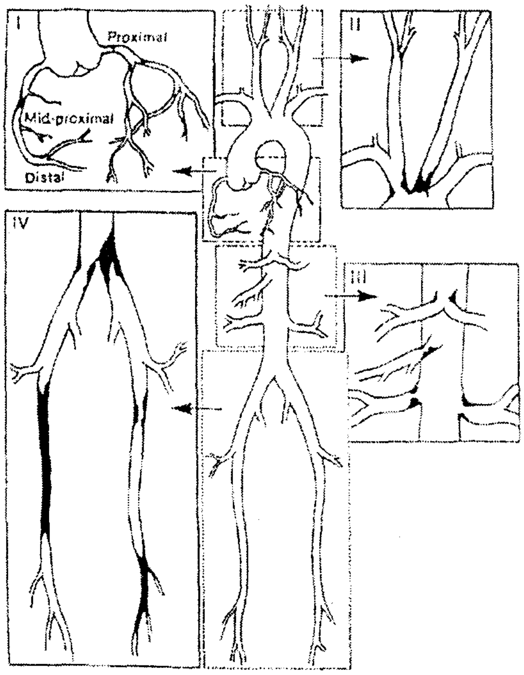
혈관의 협착(Stenosis of Arteries) : Atherosclerosis Plaque

왜 분지부(Bifurcation) 부근에서 발생하는가 ?

- Coronary Artery
- Carotid Bifurcation
- Abdominal Aorta
- Femoral Arteries

왜 특정인에게 발생하는가 ?

왜 재협착(Restenosis)현상이 발생하는가 ?



Major Factors Related to the Stenosis

(1) Fluid : Blood

(2) Hemodynamic Forces :
- Pressure Force
- Shear Force

(3) Wall and Surface :
- Blood Vessels
- Endothelial Cells

(4) Biochemical Reactions
- Blood Cells
- Micronutrients

Blood Flow : 혈액순환촉진제

• 혈액순환이 잘 된다.

- 실험적 근거 확보 ?
  In-vitro experiment
  In-vivo experiment

- 임상적 관찰결과 확보 ?

- 환자의 증언 ?

혈액순환 촉진 가능성

(1) 혈액의 조성변화 : RBC, WBC, Platelet, Plasma, Others, ---

(2) 혈액의 점성변화 : Viscosity, Rheological Characteristics, ---

(3) 혈관 벽조직의 변화 : Vessel Wall, Cells, ---

(4) 혈관통로의 확장 : Lumen Diameter, Geometry, ---

(5) 심장의 펌핑기능 향상 : Heart, Coronary Arteries, ---

혈액의 조성(Guyton)

RBC ; Mean Diameter = 7.5 μm
Average Volume = 83 μm^3
Hematocrit

WBC

Platelet

Plasma

Others

Canine Cardiovascular Parameter(Nichols & O'Rourke)

Blood Vessel	Inside Diameter	Reynolds Number
Ascending Aorta	15 mm	4500
Descending Aorta	13 mm	3400
Abdominal Aorta	9 mm	1250
Femoral Artery	4 mm	1000
Carotid Artery	5 mm	-
Arterioles	0.05 mm	0.09
Capillaries	6 μm	0.001
Venules	0.04 mm	0.035

Blood Flow Characteristics

Depending on the Size of Blood Vessels

- Blood Flow as a Continuum

  : Blood flow in large arteries and veins

- Blood as a Solution with Suspensions

  : Small arterioles and capillaries

Blood Flow as a Continuum

- Newtonian Fluid Flow

  Simple shear flow, τ = shear stress

  $\tau = \mu \frac{du}{dy}$, μ = constant(viscosity)

  Poiseuille Law, $Q = \frac{\pi \nabla p D^4}{128 \mu L}$

- Non-Newtonian Fluid Flow

  Non-linear characteristics : $\mu = \mu(\dot{\gamma})$, $\dot{\gamma}$ = shear rate

  Viscoelasticity : Characteristics of viscous and elastic properties

Classification of Non-Newtonian Fluids(Metzner)

(1) The generalized Newtonian Fluids
- Power-law fluid
- Viscosity : shear rate dependent

(2) Time Dependent Fluids
- Fluids with suspending particles

(3) Viscoelastic Fluids
- Viscous property : shear stress
- Elastic property : normal stress

(4) More Complex Fluids
- Not belong to above category

Recent Report : Blood Viscoelasticity

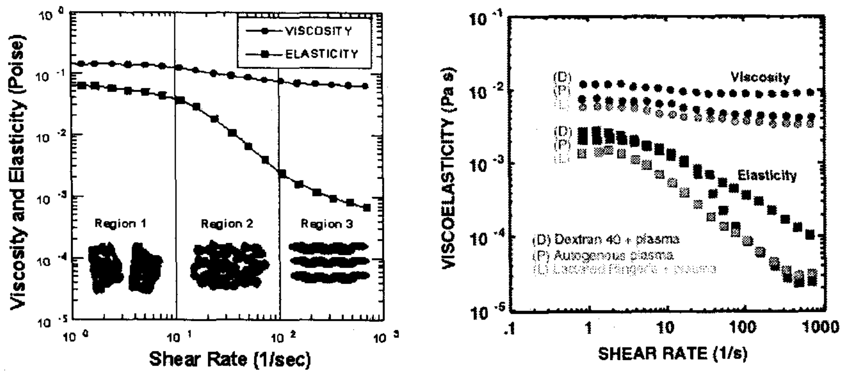
Plasma Viscosity : Newtonian fluid

Viscoelasticity :

RBC Deformability

RBC Aggregation

Hematocrit



Hemodynamic Forces in the Circulatory System

Pump : Heart

Flow Channel : Blood Vessels

Aorta – Arteries – Arterioles – Capillaries – Venules – Veins

Forces on the Walls :

- Pressure Force
- Shear Force

Hemodynamic Hypothesis Related to Atherosclerosis

(1) High Pressure : Aneurysm

(2) Low Wall Shear Stress

(3) High Wall Shear Stress

(4) High Wall Shear Stress Gradient

(5) Flow Abnormalities(Turbulent flow)

Analysis of Blood Flow Phenomena

Pulsatile Flow : Unsteady Flow(Systole and Diastole)

Non-Newtonian Fluid :

- Generalized Newtonian Fluid
- Viscoelastic Fluid

Moving Boundary

- Elastic Wall
- Viscoelastic Wall

Governing Equations

Continuity Equation

$$\frac{\partial u_j}{\partial x_j} = 0$$

Momentum Equations

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

Stress Tensor and Rheological Equation

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

μ : Given by the Constitutive Equation

Constitutive equations for the viscosity of blood

Models	Constitutive Equations	Constants
Powell-Eyring Model, Powell and Eyring [1944]	$\mu = \mu_\infty + (\mu_0 - \mu_\infty)\left[\frac{\sinh^{-1}\lambda\dot{\gamma}}{\lambda\dot{\gamma}}\right]$	λ = 5.383 s, μ_0 = 0.56 poise, μ_∞ = 0.0345 poise
Modified Powell-Eyring Model, Cho and Kensey [1989]	$\mu = \mu_\infty + (\mu_0 - \mu_\infty)\frac{\ln(\lambda\dot{\gamma}+1)}{[\lambda\dot{\gamma}]^m}$	λ = 2.415 s, m = 1.089, μ_0 = 0.56 poise, μ_∞ = 0.0345 poise
Simplified Cross Model, Steffan et al. [1989]	$\mu = \mu_\infty + (\mu_0 - \mu_\infty)\frac{1}{1+(\lambda\dot{\gamma})}$	λ = 8.0 s, μ_0 = 1.30 poise, μ_∞ = 0.05 poise
Modified Cross Model	$\mu = \mu_\infty + (\mu_0 - \mu_\infty)\frac{1}{\left[1+(\lambda\dot{\gamma})^m\right]^a}$	λ = 3.736 s, m = 2.406, a = 0.254, μ_0 = 0.56 poise, μ_∞ = 0.0345 poise
Carreau Model, Bird et al. [1987]	$\mu = \mu_\infty + (\mu_0 - \mu_\infty)\left[1+(\lambda\dot{\gamma})^2\right]^{\frac{n-1}{2}}$	λ = 3.313 s, n = 0.3568, μ_0 = 0.56 poise, μ_∞ = 0.0345 poise
Casson Model, (Nakamura and Sawada [1988], Cokelet[1972], Walawender[1975])	$\sqrt{\tau} = \sqrt{k_0} + \sqrt{k_1\dot{\gamma}}$	k_0 = 0.05 dyne/cm^2, k_1 = 0.04 dyne s/cm^2
Power-Law Model, (Bird et al. [1987], Moravec and Liepsch[1983], Davies et al.[1990])	$\tau = m(\dot{\gamma})^n$	n = 0.61, m = 0.42, n = 0.60, m = 0.35 if $\dot{\gamma} \le 226.5\ s^{-1}$ μ = 0.04 poise if $\dot{\gamma} > 226.5\ s^{-1}$

Some Results for the Bifurcation Flows

Governing Equations

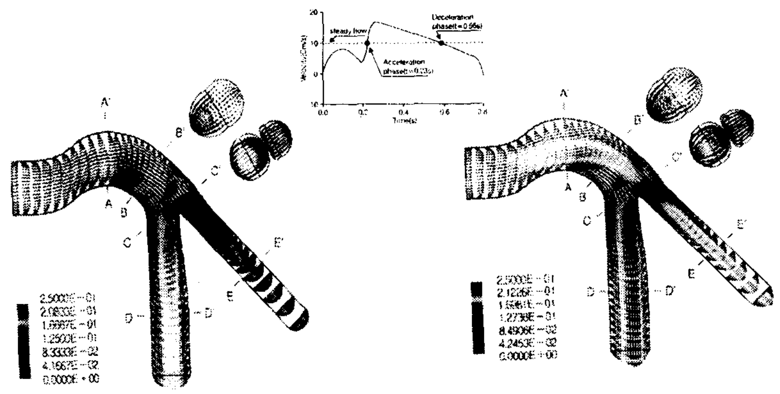
$$\frac{\partial u_j}{\partial x_j}=0$$

$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\mu_e\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$$

Rheological Equation : Carreau Model

$$\mu_e=\mu_\infty+(\mu_0-\mu_\infty)\left[1+(\lambda\dot{\gamma})^2\right]^{\frac{(q-1)}{2}}$$

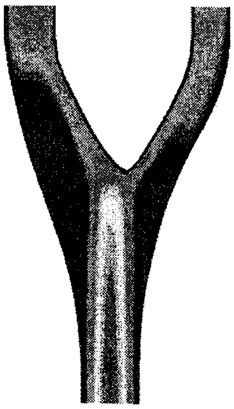
Coronary Artery



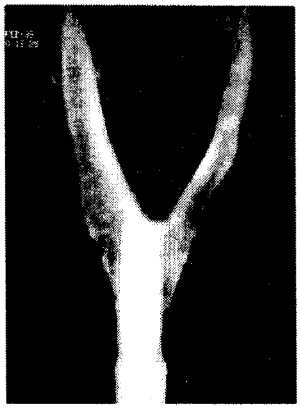
acceleration phase (t=0.23s)

deceleration phase (t=0.56s)

Carotid Artery

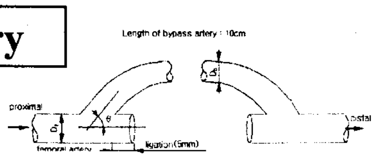


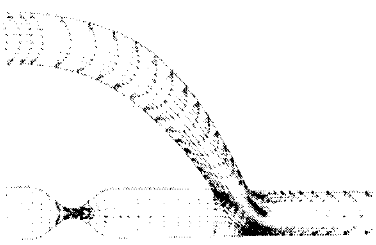
Velocity shadow contour



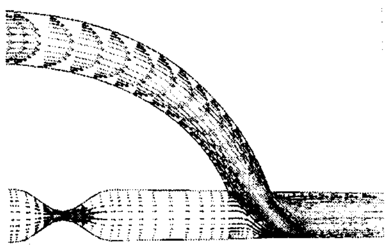
MRA image

Graft Artery





45 deg



60 deg

Flow Characteristics in the Bifurcated Region

(1) Unsteady Flow
Oscillation

(2) Reversed Flow
Flow Separation

(3) Secondary Flow

(4) Unstable Turbulent Flow

Hemodynamic Force Effects

Localization of Atherosclerosis

Cell Biology
- Smooth Muscle Cells
- Endothelial Cells

Secretion of Molecules
- Nitric Oxide
- Prostacyclin(PG12)
- Tissue Plasminogen Activator(tPA)

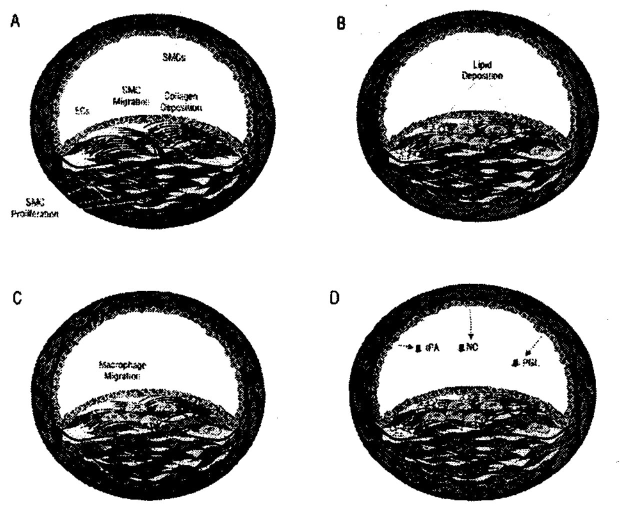
Major Risk Factors of Heart Disease (AHA): General

(1) Increasing age
(2) Gender
(3) Heredity(Race)
(4) Smoking
(5) High Blood Cholesterol
(6) High Blood pressure
(7) Physical inactivity
(8) Obesity and Overweight
(9) Diabetes

Cardiovascular Risk Factors (SpectraCell Lab.) : Micronutrients

(1) Elevated homocysteine status
(2) Elevated fibrinogen status
(3) Elevated LDL cholesterol
(4) Elevated lipoprotein status
(5) Elevated c-reactive protein status
(6) Elevated apoliprotein B status
(7) Low apoliprotein A-1
(8) Low apoliprotein B
(9) Low HDL cholesterol

A Cross Section of a Blood Vessel



Needs for Advanced Research

Measurement of Blood Property
- In-vitro measurement
- In-vivo measurement

Clinical Application of Blood Properties
- Diagnosis
- Diabetes

Effects of Stress and Strain on
- Cell Proliferation
- Secretion of molecules

Effects on Mechanical Forces on
- Signal transduction pathways

Application of the Hemodynamic Principles for Biomedical Devices

- Ultrasonic Device
- CT
- MRI
- Miniaturized Probes
- Computer Interfaced Sensors

• Hemodynamic Principles are used

• Devices will be highly developed by Computer + Optics + Nano Technologies

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