혈류역학적 전단응력이 혈관내피세포에 미치는 영향

: 전산유체역학을 이용한 혈류역학적 연구

2003. 4. 26.

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이병권(인제대 상계백병원 내과)

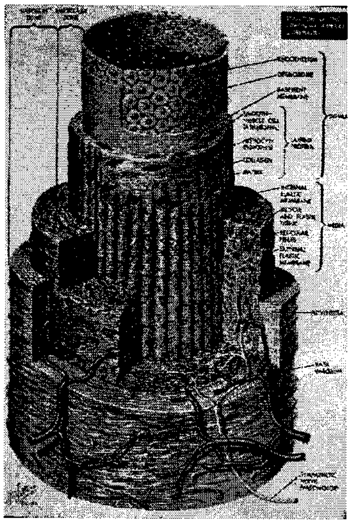
생체유체역학 연구분야

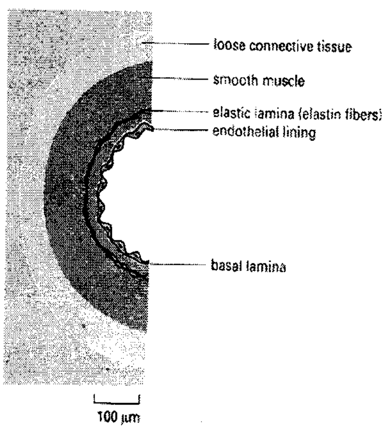
- o 혈류역학적 연구
  - o Stenosis나 Aneurysm을 통한 유동
  - o 분지관 유동
  - o Heart-Valve 유동
  - o 문합부 유동
- o 혈관내피세포에 관한 연구 (microcirculation)
  - o 혈관내피세포의 생화학적 특성
  - o 혈관내피세포의 형태변화
  - o 혈구와 혈관내피세포사이의 점착관계
- o 동맥혈관벽에 관한 연구
  - o 맥동유동에 의한 혈관벽의 변화
  - o Compliance Mismatch

혈관내피세포 관련연구

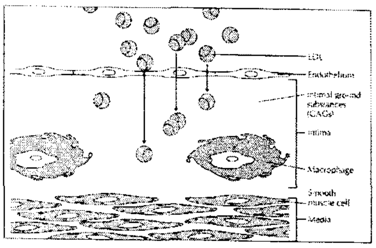
- o Satcher. R. L. et al. (1992)
  - EC의 형상을 수학적모델링하고 수치해석 수행
- o 장준근(1995), 정찬일(1997)
  - In vitro 실험으로 전단유동에 의한 혈관내피세포의 형태변화
- o Peter F. D. et al. (1997)
  - EC의 신호체계 연구 (Mechanotransduction)
- o 서상호, 유상신(1996-2000)
  - 컴퓨터 시뮬레이션으로 EC의 형태변화
- o Shuichiro, F. et al. (1999)
  - PTV 기법으로 EC Model 주위 유동 가시화

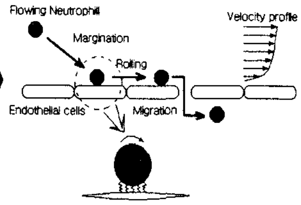
동맥혈관벽의 구조

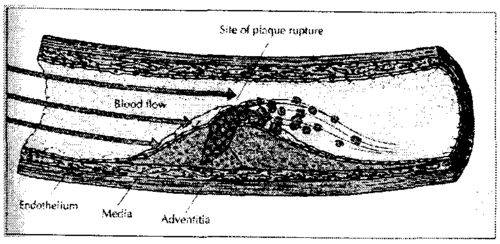




동맥경화의 생성





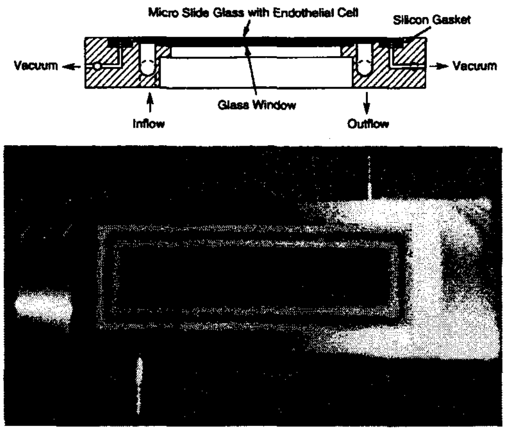


혈관내피세포의 특성

- 단일층의 혈액접촉면 형성,
- 혈액내 신경호르몬이나 기계적 자극에 반응
- 생체내 혈관내피세포는 유동방향으로 정렬
- 유동장 교란 ⇒ 형태학적 변화
  ⇒ 혈관질환과 연관
- 수직세포막 - 다른 혈관내피세포와
  - 신호전달을 원활
- 하부세포막 - 세포외기질에 점착
- 유동으로 인해 구조적 혹은 동적인 특성이 변화

혈관내피세포 관련 결과 1

(전단응력과 혈관내피세포의 형상변화)



$$\tau = 6\frac{\mu Q}{bh^3}$$

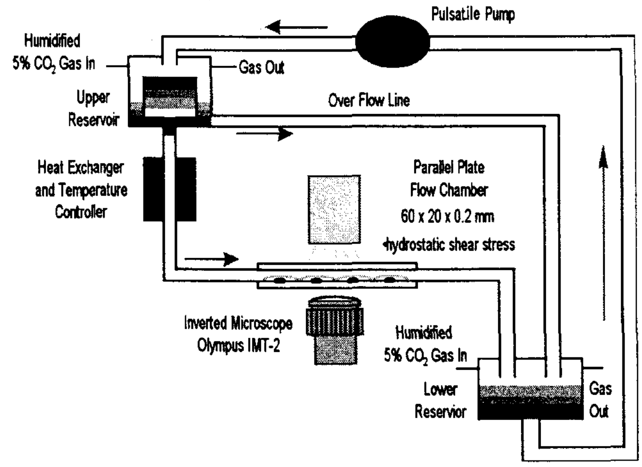
b = 2.0 cm, h = 0.02cm

μ= 0.7 cp, Q = 0.2857 ml/s

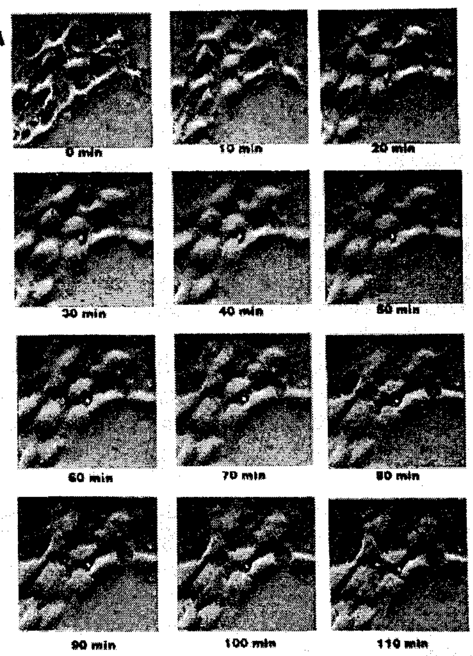
τ= 15 dyne/cm^2

Exposure time :
5, 10, 20, 40, 60 min

혈관내피세포의 형상 획득



Shear-induced morphological changes of endothelial cells for 2 hour

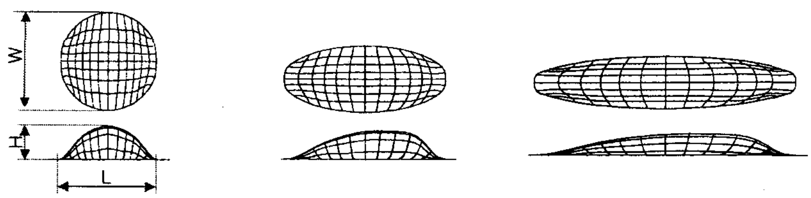


혈관내피세포 관련 결과 2

(혈관내피세포 주위의 혈류역학적 특성)

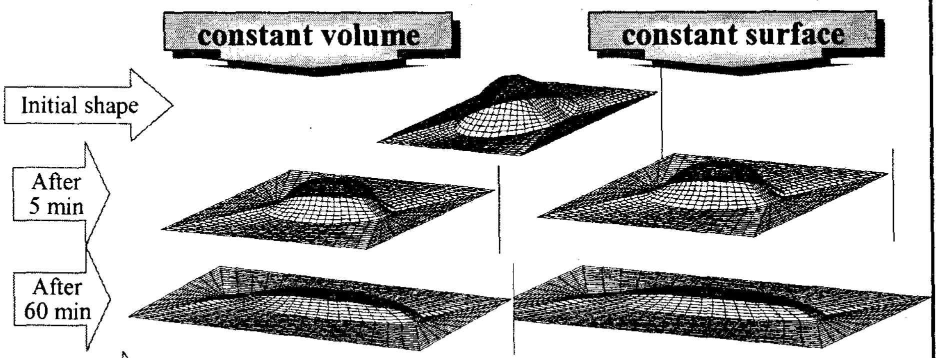
Micrographs of the Endothelial Cells

(a) initial shapes(0 min) (b) shapes after 5 min (c) shapes after 60 min



L×W×H = 30×30×10 μm L×W×H = 42×17×5.6 μm L×W×H = 70×10×4 μm

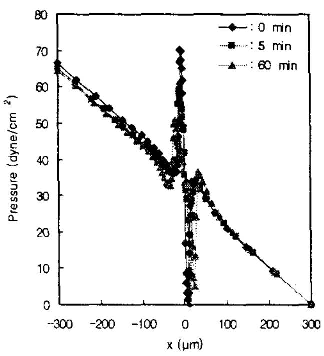
Dimensions of the endothelial cells



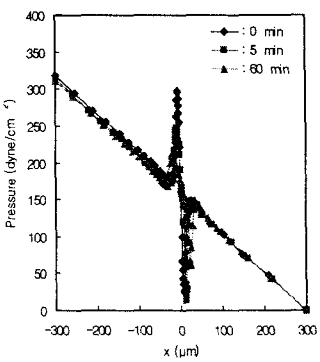
Dimensions

Time	Condition	Hight	Length	Width
initial	constant surface	8.46	25	25
	constant volume	8.46	25	25
after 5 min	constant surface	7.20	35.38	17
	constant volume	7.75	38.09	18.30
after 60 min	constant surface	3.93	63.39	9.77
	constant volume	4.99	80.43	12.40

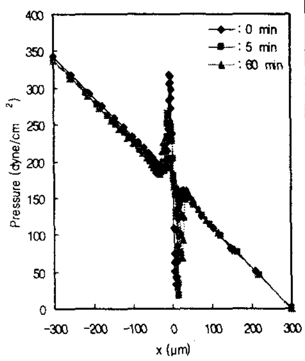
Pressure distributions



(a) Newtonian fluid(μ= 0.7 cp)

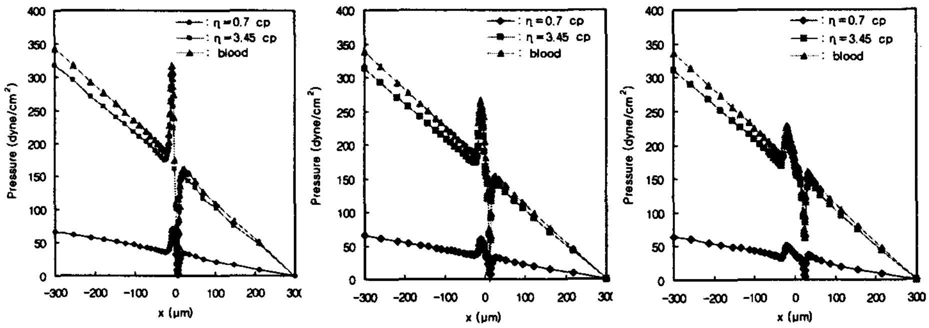


(b) Newtonian fluid(μ= 3.45 cp)



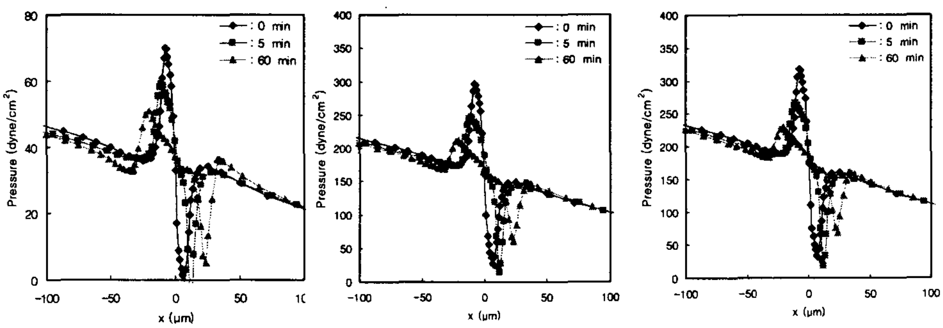
(c) Blood

Pressure distributions



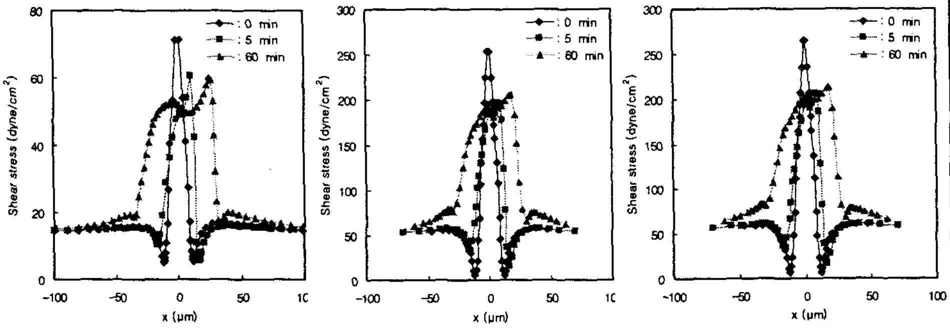
(a) Newtonian fluid(μ= 0.7 cp) (b) Newtonian fluid(μ= 3.45 cp) (c) Blood

Pressure distributions



(a) Newtonian fluid(μ= 0.7 cp) (b) Newtonian fluid(μ= 3.45 cp) (c) Blood

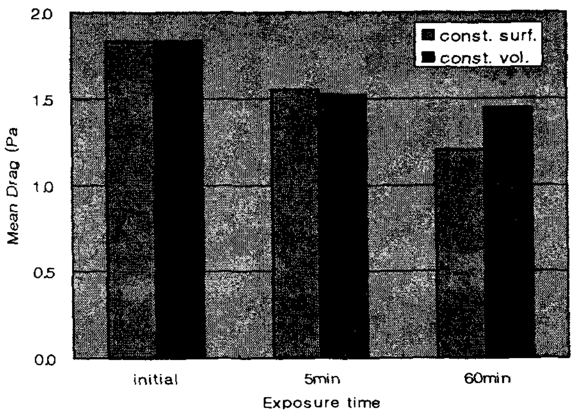
Wall shear stress distributions



(a) Newtonian fluid(μ= 0.7 cp) (b) Newtonian fluid(μ= 3.45 cp) (c) Blood

Mean drag with different exposed times

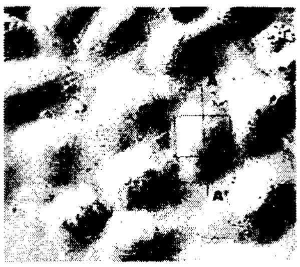
$$\text{Drag}_{\text{mean}} = \frac{\int(-\text{p}\cos\theta - \tau_w \sin\theta)\text{dA}}{\text{Cell Surface}}$$

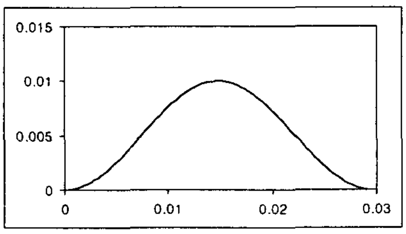


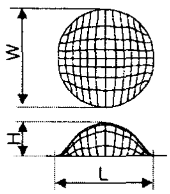
혈관내피세포 관련 결과 3

(혈관내피세포주위의 유동가시화)

Three-Dimensional Shape for the EC







L×W×H = 30×30×10 μm

- ✓ Simple Cosine Function
- ✓ Scale of Width and Length is same

$$y_{shape} = 0.005\left[1-\cos\left(\frac{2\pi x}{0.025}\right)\right]$$

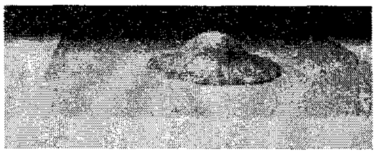
혈관내피세포 모형제작

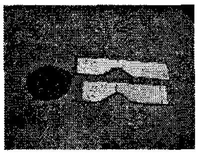
Minimum thickness of sheet beam for PIV : 2mm

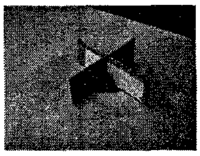
Minumum height for PIV : 1 cm

Apply Similarity Law

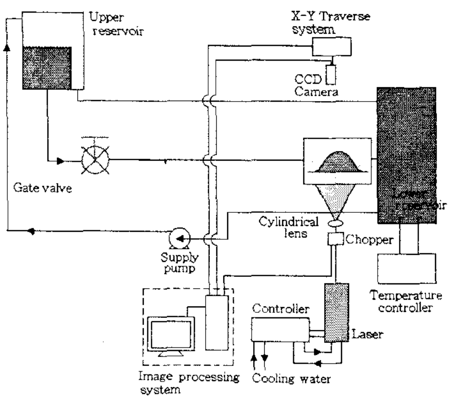
Magnify a thousand times for the actual size of 10 ㎛

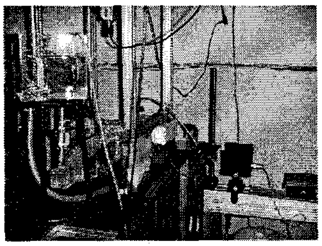


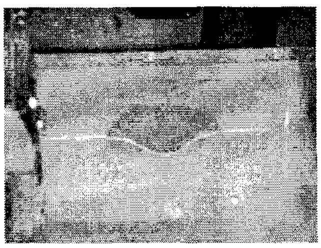




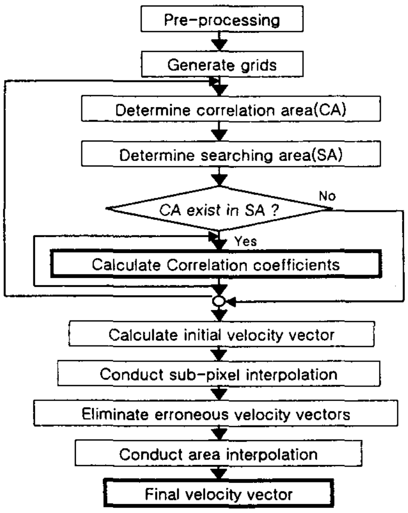
실험장치



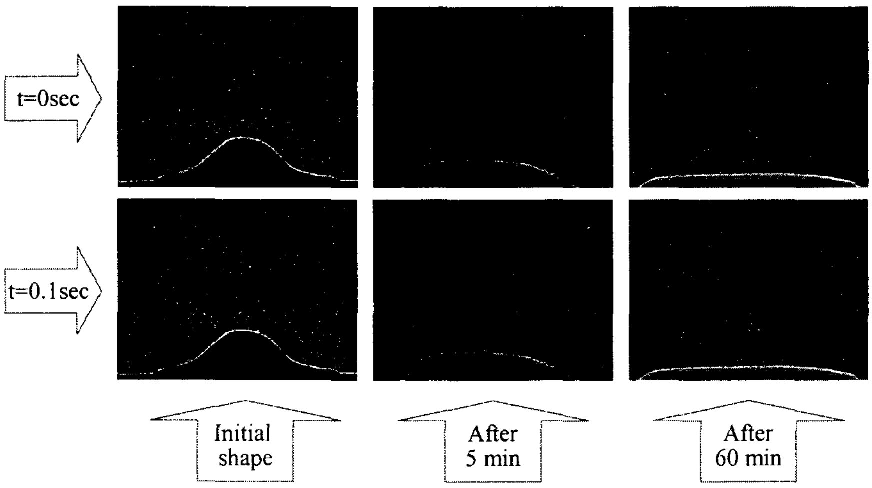




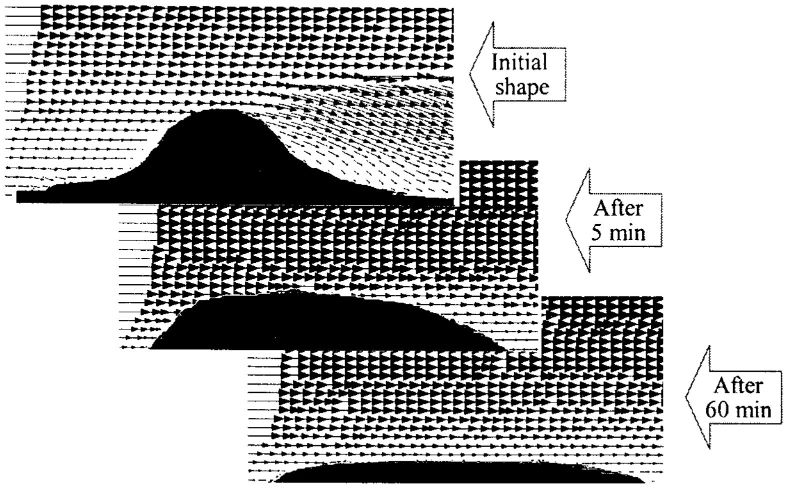
이미지 처리 알고리즘



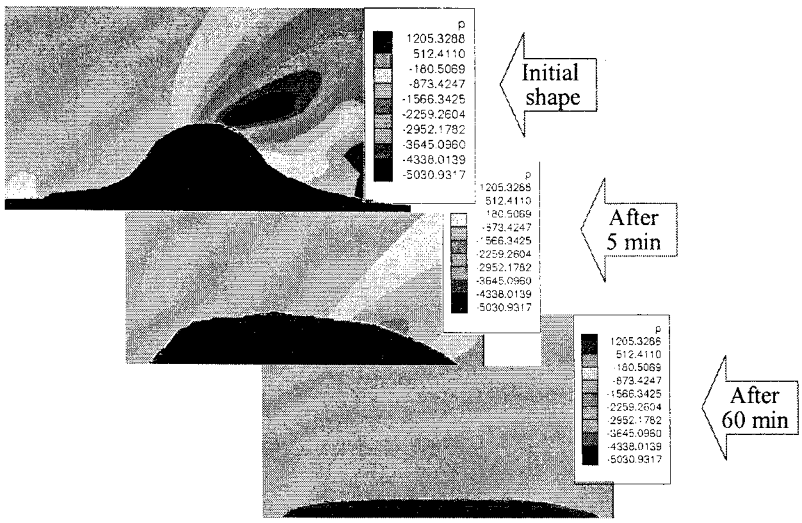
원시영상



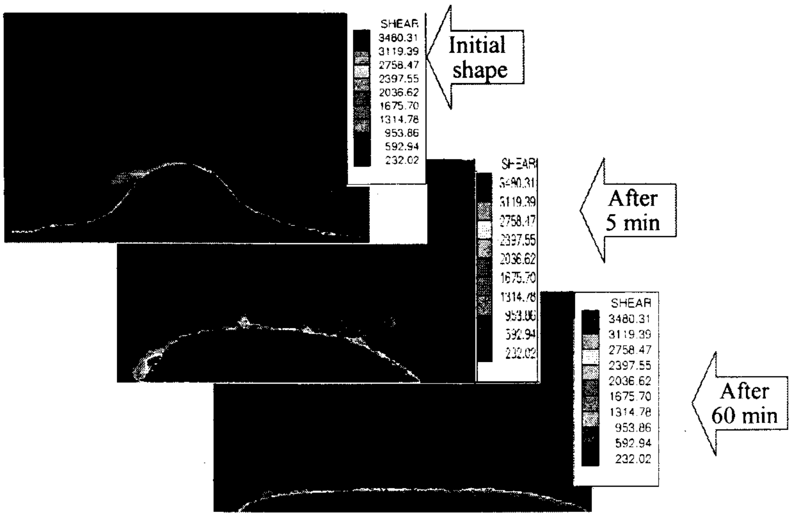
속도벡터


Initial shape
After 5 min
After 60 min

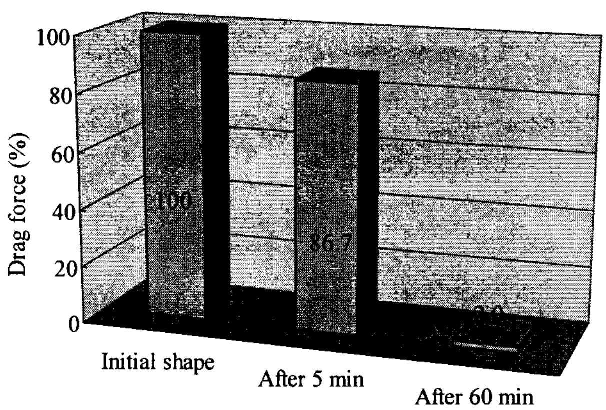
압력분포


p
1205.3288
512.4110
-180.5069
-873.4247
-1566.3425
-2259.2604
-2952.1782
-3645.0960
-4338.0139
-5030.9317
Initial shape
p
1205.3288
512.4110
-180.5069
-873.4247
-1566.3425
-2259.2604
-2952.1782
-3645.0960
-4338.0139
-5030.9317
After 5 min
p
1205.3288
512.4110
-180.5069
-873.4247
-1566.3425
-2259.2604
-2952.1782
-3645.0960
-4338.0139
-5030.9317
After 60 min

전단율 분포


SHEAR
3480.31
3119.39
2758.47
2397.55
2036.62
1675.70
1314.78
953.86
592.94
232.02
Initial shape
After 5 min
After 60 min

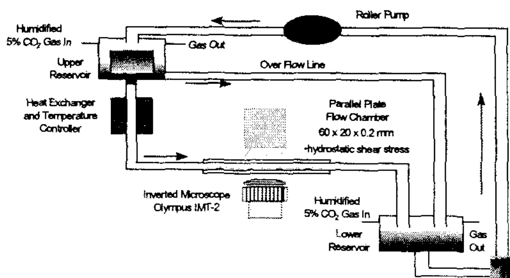
항 력


Drag force (%)
100
80
60
40
20
0
100
86.7
Initial shape
After 5 min
After 60 min

혈관내피세포 관련 결과 4

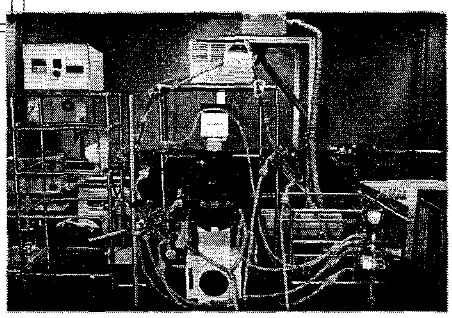
(복잡한 유동장내의 혈관내피세포의 형태변화)

Flow Chamber Experimental Setup.



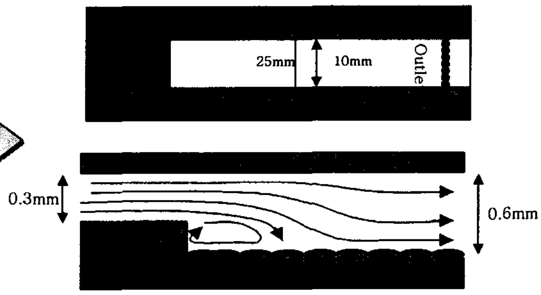
Schematic view of flow chamber system

Photography of flow chamber system

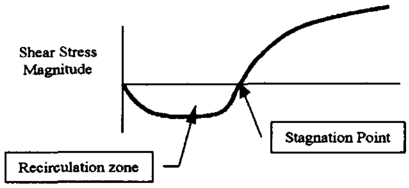


Sudden expansion flow chamber

Schematic of flow pattern

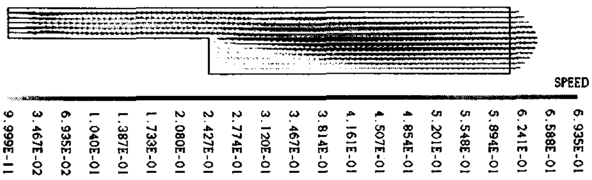


Estimated shear stress



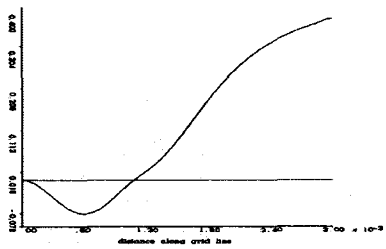
Lateral variation in shear stress

Velocity vector

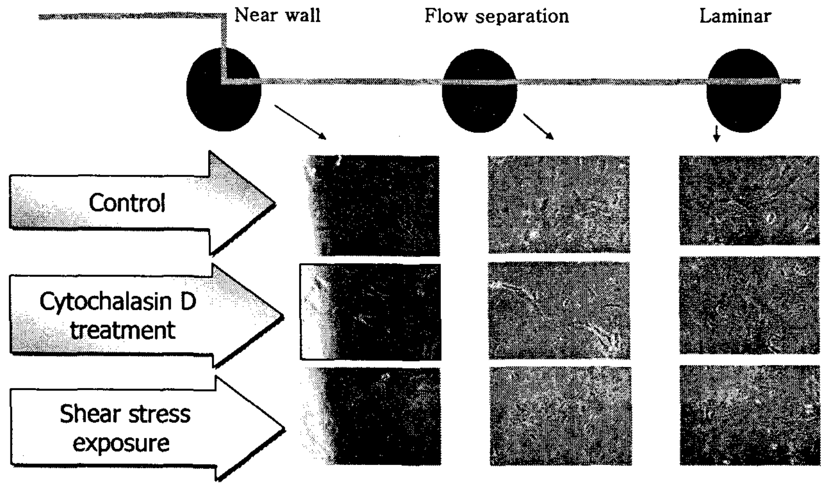


Streamline

Shear stress through the EC seeding plate

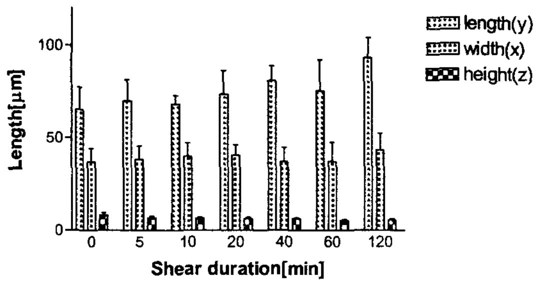


Microscopic view of endothelial cells

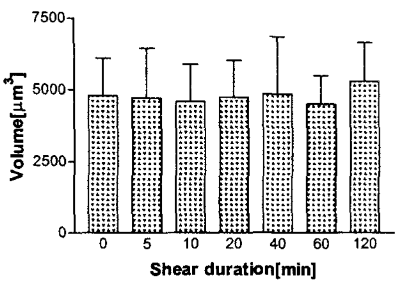


Time history of morphological change

length, height, width



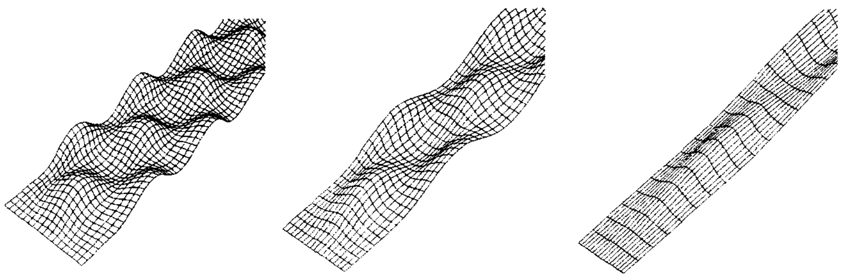
Volume of exposed endothelial cell under shear stress (20dyne/cm2)



혈관내피세포 관련 결과 5

(혈관내피세포 주위의 맥동유동특성)

혈관내피세포의 모델링



Initial shape(0 min)　Shapes after 5 min　Shapes after 60 min

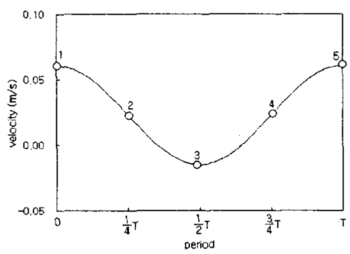
혈관내피세포의 모델링

(unit : ㎛)

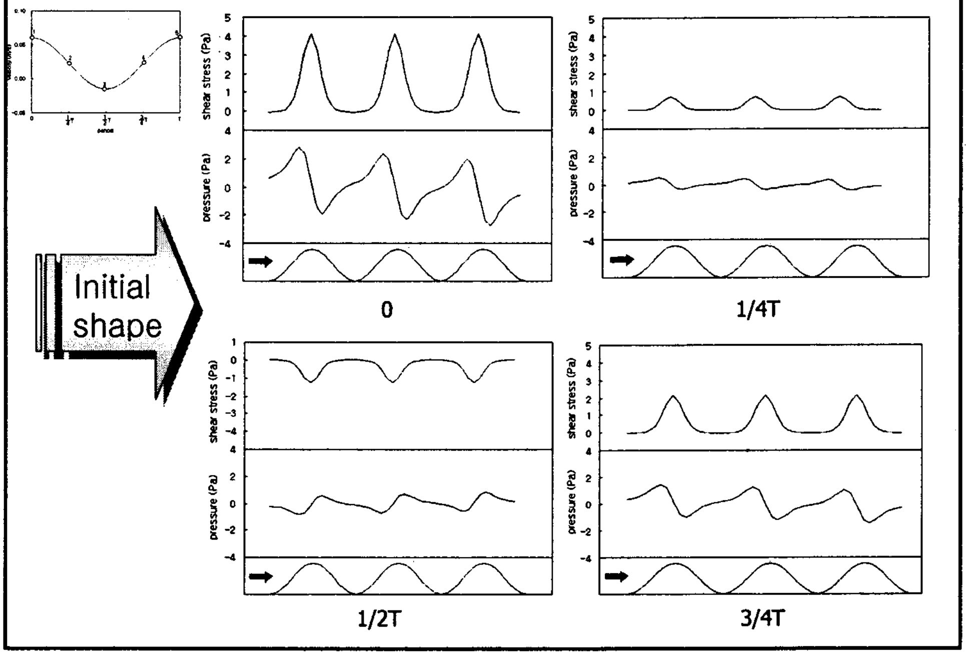
Time	Height	Length	Width
initial	8.46	25	25
after 5 min	7.72	38	18
after 60 min	5.02	81	13

경계조건

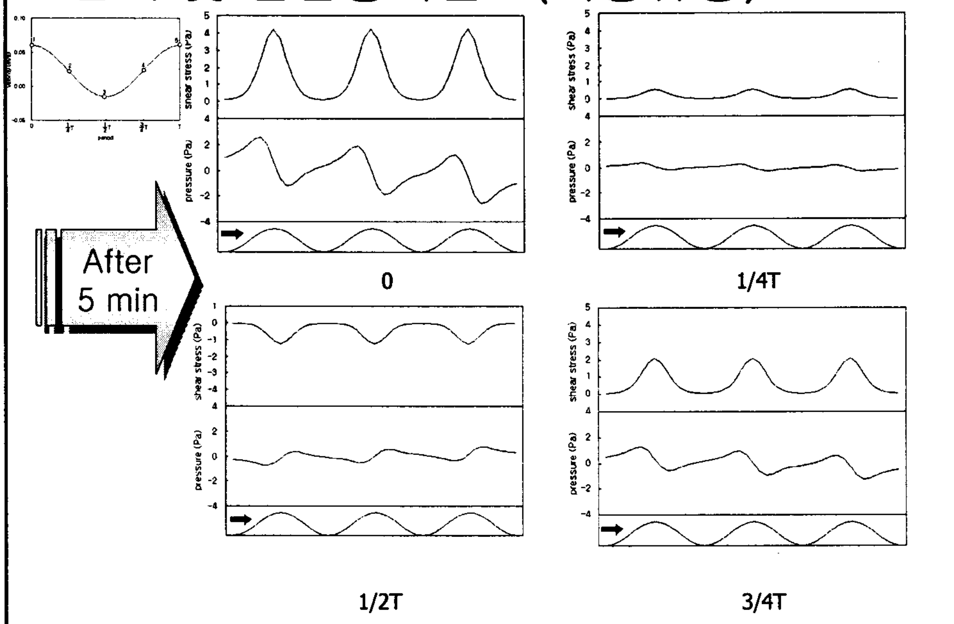
- Inlet B.C.
  - 대퇴동맥(femoral artery)에서 Duplex Scan image로부터 구한 속도파형
  - 주기 : 45bit/min
- Outlet B.C.
  - Pressure B.C.
- Side
  - Symmetric B.C.



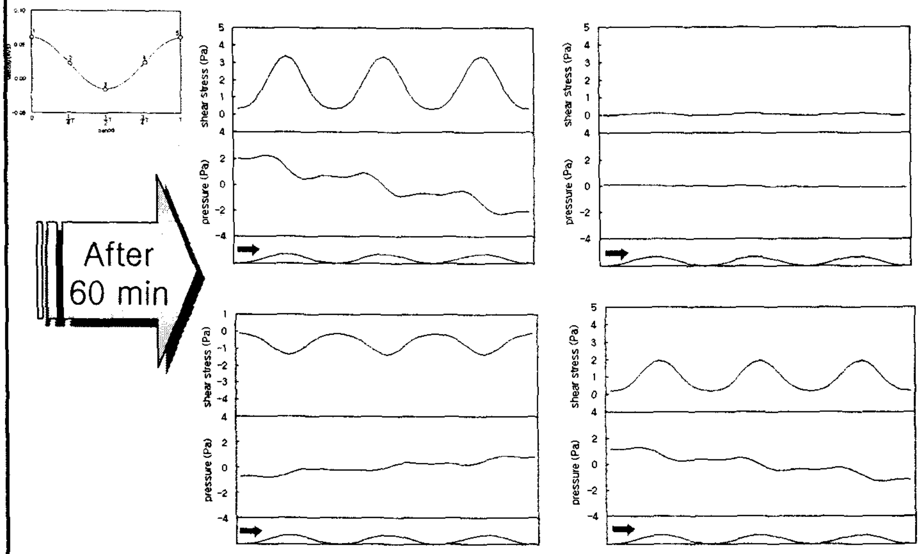
압력 및 전단응력분포(맥동유동)



압력 및 전단응력분포(맥동유동)



압력 및 전단응력분포(맥동유동)



평균항력

$$Drag_{mean} = \frac{\int(-p\cos\theta - \tau_w \sin\theta)dA}{\text{Cell Surface}}$$