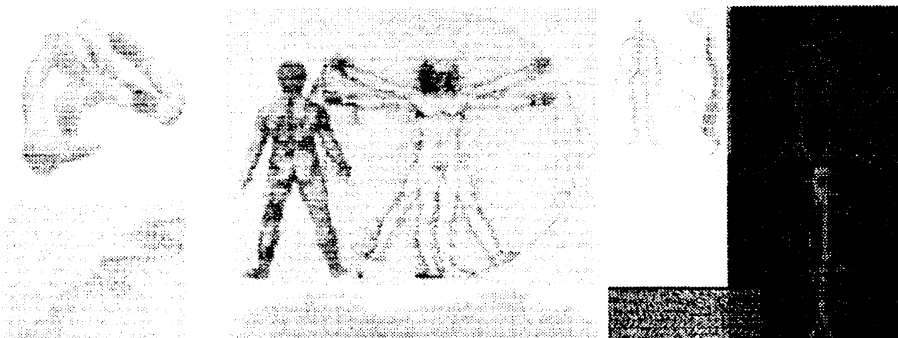# Computational biomechanics:
from animal locomotion to the cardiovascular system

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Graduate School of Engineering

Chiba University, JAPAN

2008.2.18-20   Kyoto Workshop on
                                      Computational Fluids

Why Computational Biomechanics

Physiom of Circulatory system

Biological systems and hence biomechanics are, in general, "complex systems", which need to be modeled as realistically as possible so that we can avoid some pitfalls.
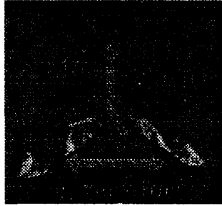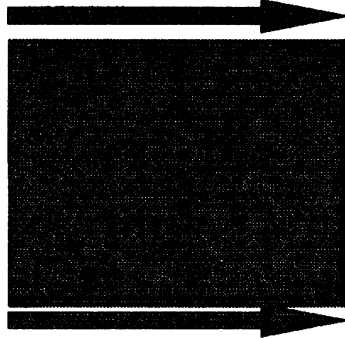
An 'alive' CVS modeling for the whole body

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FOUR Dynamic Phenomena in Insect Flight

Force generation
mechanisms

Flight control
mechanisms

@Complicated wing
  kinematics
@Unsteady aerodynamics in
  terms of vortex dynamics
@Low Res<10^4
@Conventional 'quasi-
  steady' theory never works

@Multi-body Dynamics with
  6DOF
@High freq. 20~1000Hz
@Dynamic flight stability
@Maneuverability

**Four Dynamics, large-scale simulation on flight dynamics,
aerodynamics, structural dynamics, and thermodynamics**

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Novel Mechanisms in Insect Flapping Flight

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Insects fly across a Re range by 4 orders (10^1 - 10^4)
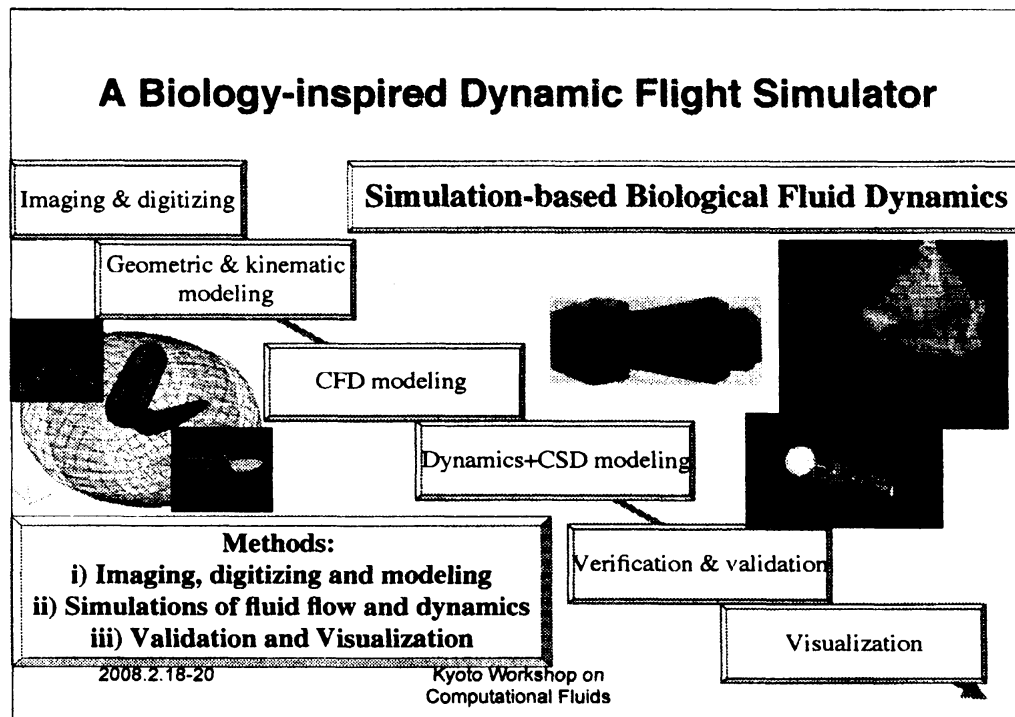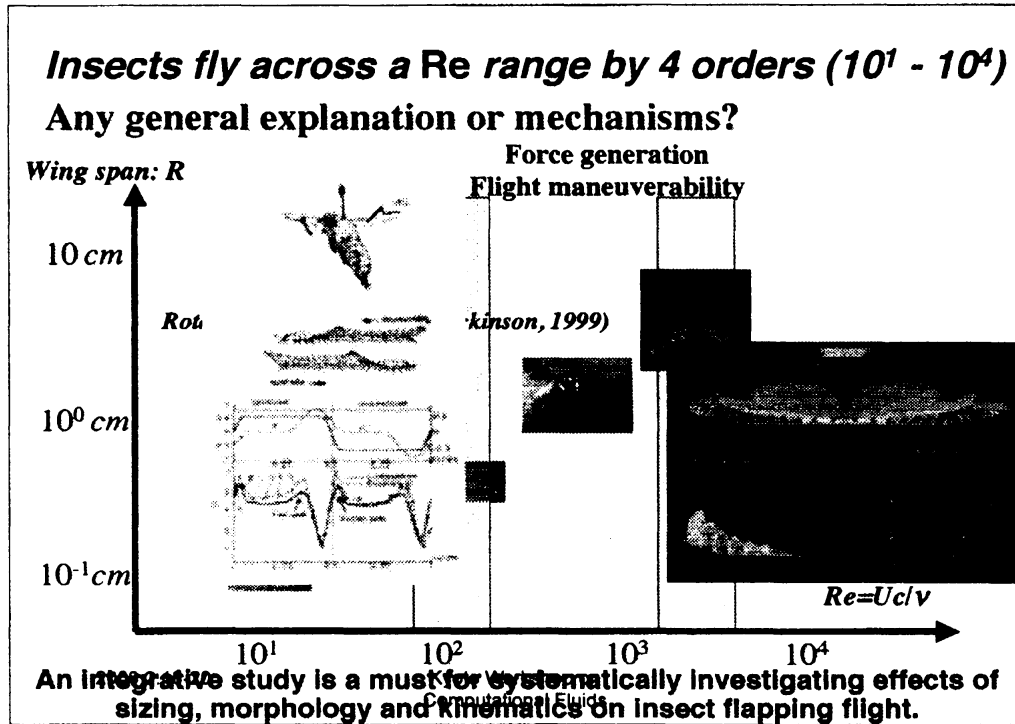
Any general explanation or mechanisms?

Force generation
Flight maneuverability

Wing span: R

$10\,cm$

Rot ·kinson, 1999)

$10^0\,cm$

$10^{-1}cm$

$Re = Uc/v$

10^1 10^2 10^3 10^4

An integrative study is a must for systematically investigating effects of sizing, morphology and kinematics on insect flapping flight.

Computational Fluids

A Biology-inspired Dynamic Flight Simulator

Imaging & digitizing | Simulation-based Biological Fluid Dynamics

Geometric & kinematic modeling

CFD modeling

Dynamics+CSD modeling

Methods:
i) Imaging, digitizing and modeling
ii) Simulations of fluid flow and dynamics
iii) Validation and Visualization

Verification & validation

Visualization

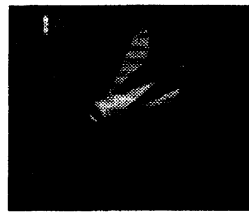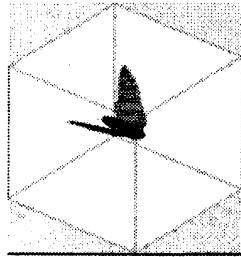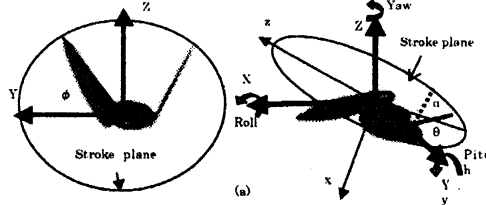2008.2.18-20   Kyoto Workshop on Computational Fluids

A Biology-inspired Dynamic Flight Simulator
continued

Aerodynamics

Energetics: Force, Moment and Power

Flight dynamics

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Pressure-gradient, Centrifugal,
and Coriolis forces

(a)

(b)
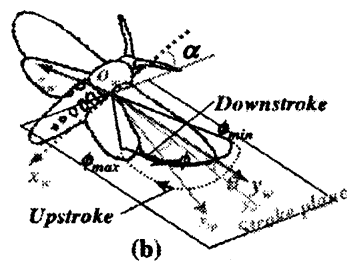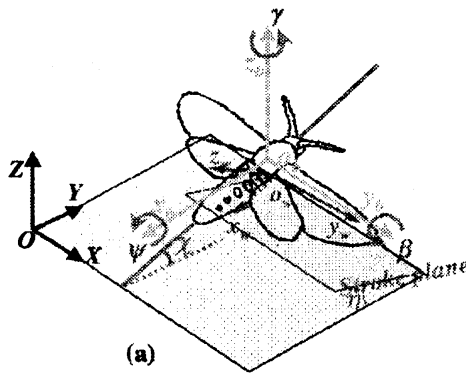
(a) Three systems: wing-fixed system (x_w, y_w, z_w), the body-fixed system (x_b, y_b, z_b), and the global system (X, Y, Z); the stroke plane angle η and the body angle χ; the angles of pitch β, roll ψ, and yaw γ with respect to the body-fixed system.

(b) Wing position parameters within the stroke plane: the wingtip path, the positional angle ϕ, the elevation angle θ, and the angle of attack α.

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$$T = \frac{dr}{ds}, N = \frac{dT}{ds} / \kappa, B = T \times N$$

Frenet-Serret formula

(a)   (b) (b)

(a) A top-view fruit fly with a computer model superimposed on the right half and a perspective view of the model with the extracted body centerline L and elliptic cross sections.

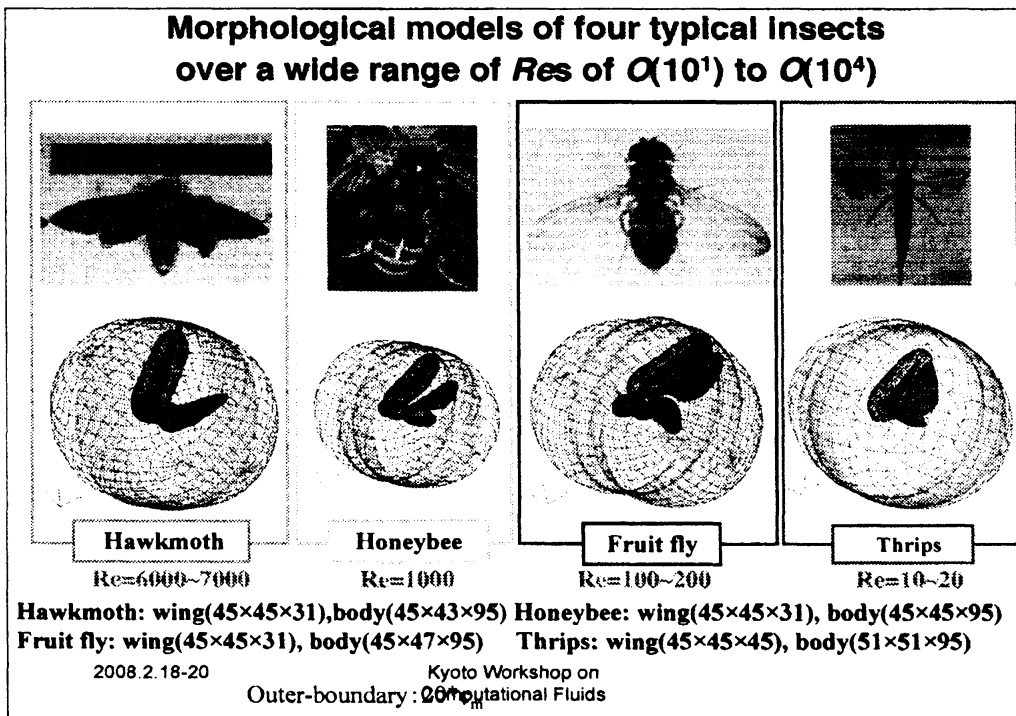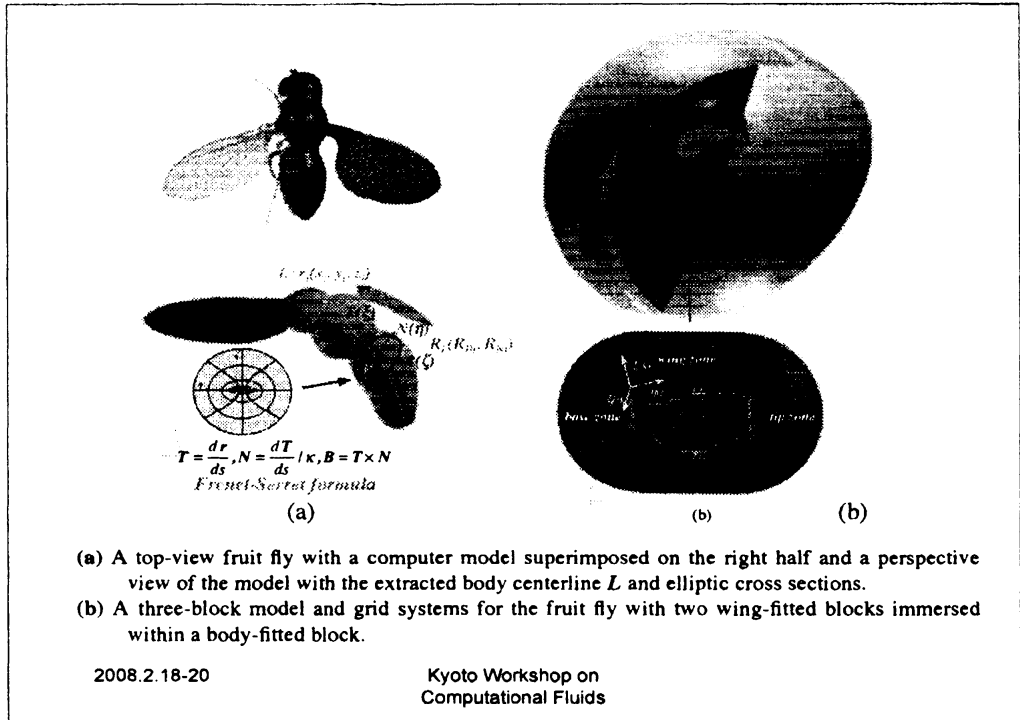(b) A three-block model and grid systems for the fruit fly with two wing-fitted blocks immersed within a body-fitted block.

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Morphological models of four typical insects
over a wide range of *Res* of $O(10^1)$ to $O(10^4)$
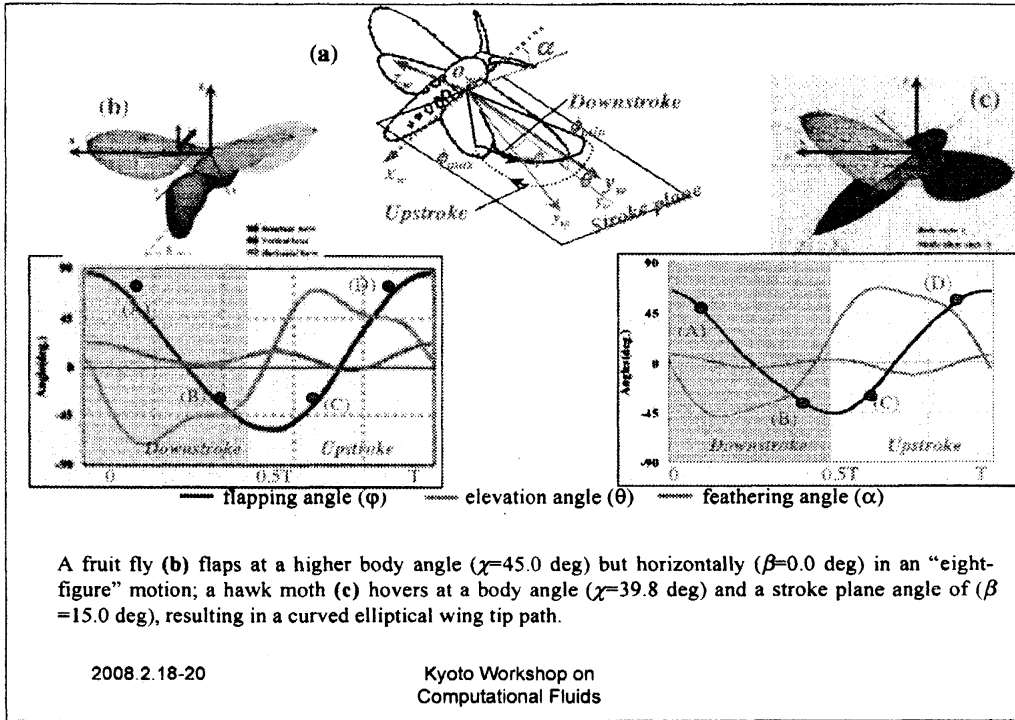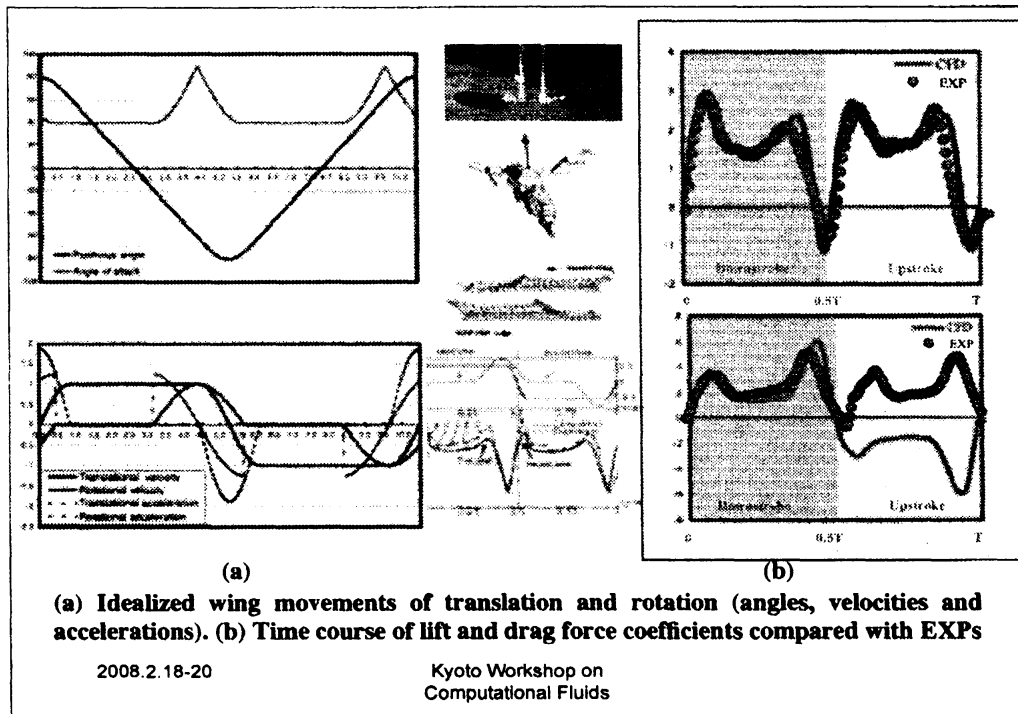
Hawkmoth **Honeybee** **Fruit fly** **Thrips**

Re=6000~7000 Re=1000 Re=100~200 Re=10~20

Hawkmoth: wing(45×45×31),body(45×43×95) Honeybee: wing(45×45×31), body(45×45×95)
Fruit fly: wing(45×45×31), body(45×47×95) Thrips: wing(45×45×45), body(51×51×95)

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Outer-boundary : 20m Computational Fluids

(a)

(b)

(c)

Downstroke

Upstroke

Stroke plane

—— flapping angle (φ) ——— elevation angle (θ) ——— feathering angle (α)

A fruit fly **(b)** flaps at a higher body angle (χ=45.0 deg) but horizontally (β=0.0 deg) in an "eight-figure" motion; a hawk moth **(c)** hovers at a body angle (χ=39.8 deg) and a stroke plane angle of (β =15.0 deg), resulting in a curved elliptical wing tip path.

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　　　　　　　　　　Computational Fluids

Kinematic models of four typical insects

·Hawkmoth[1]

·Honeybee[2]

·Fruit fly[3]

·Thrips[4] (a fly-like kinematic model)

(1) A.P. Willmott., et al, *JEB*; 200 2705-2722 (1997)
(2) D.L. Altshuler., et al, *PNAS*; vol.102; no.50; 18213-18218 (2005)
(3) N.S. Fry, et al,, *JEB*; 208, 2303-2318 (2005)
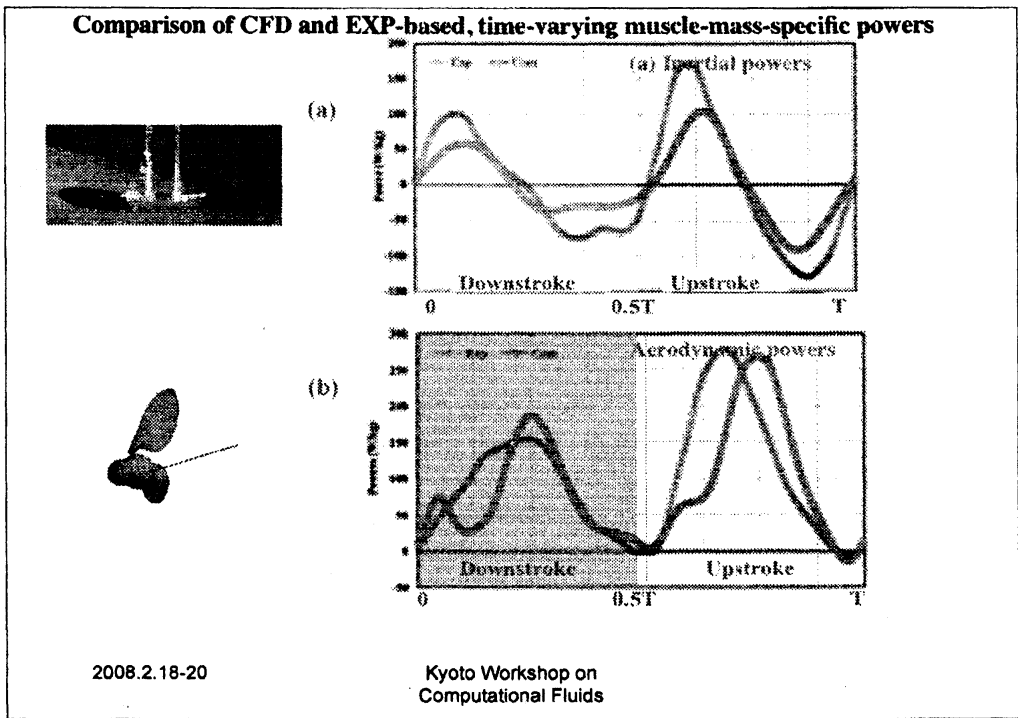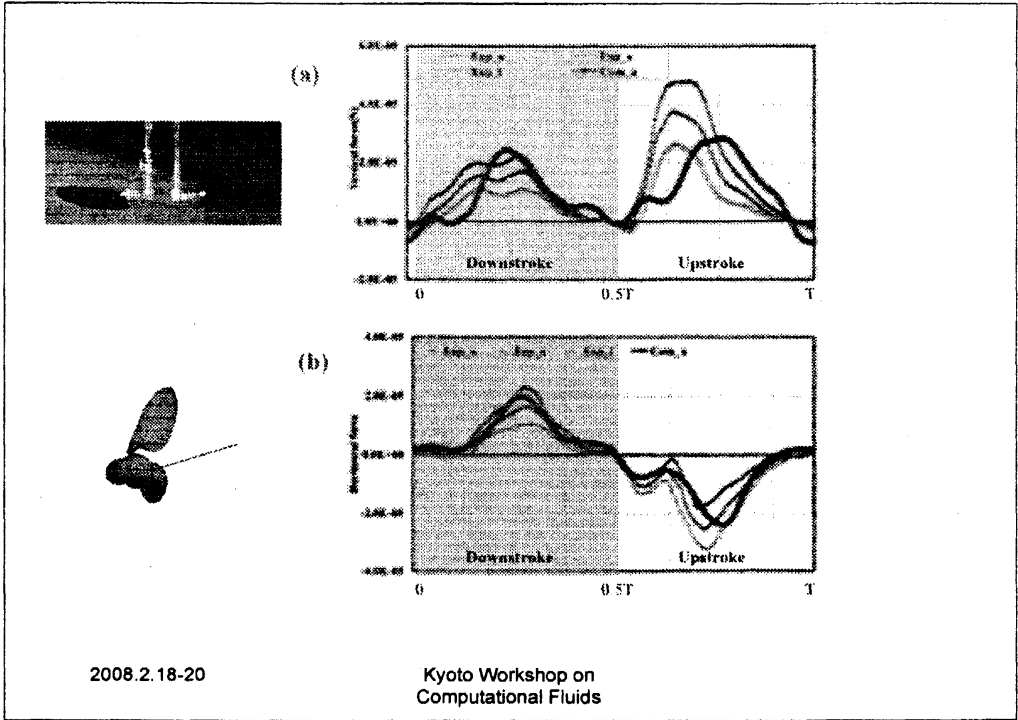(4) F.O. Lehmann, et al, *JEB*; 208, 3075-3092, (2005)

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　　　　　　　　　　Computational Fluids

Weights and computed lift forces (*mN*) in hovering flights of hawkmoth, honeybee and fruitfly.
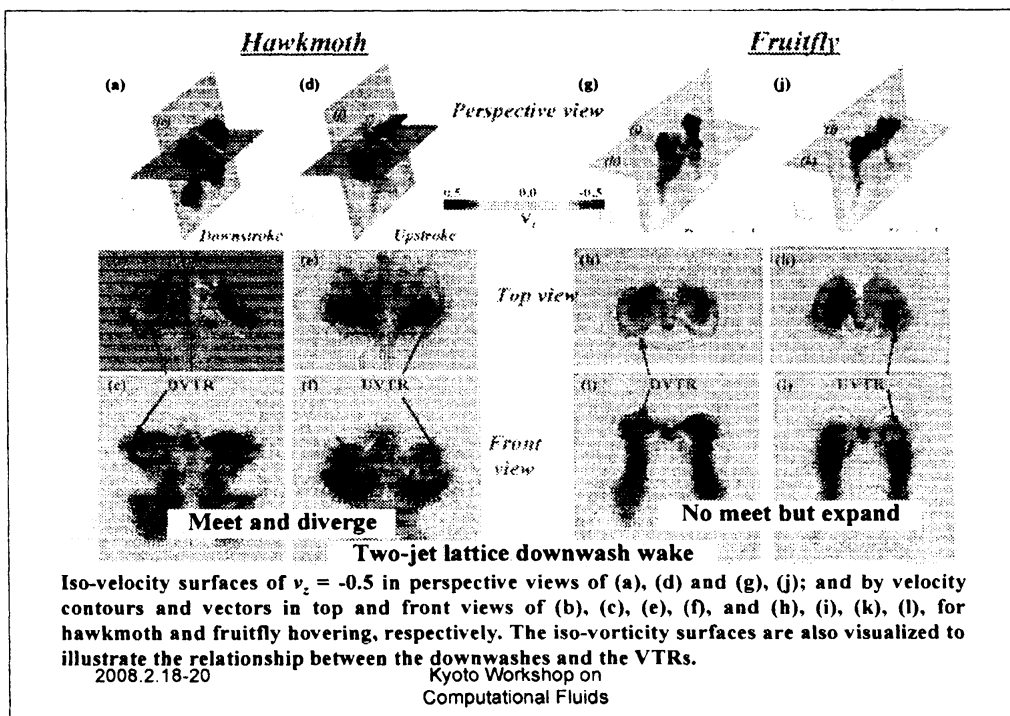
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(a)   (b)

(a) Idealized wing movements of translation and rotation (angles, velocities and accelerations). (b) Time course of lift and drag force coefficients compared with EXPs

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(a)

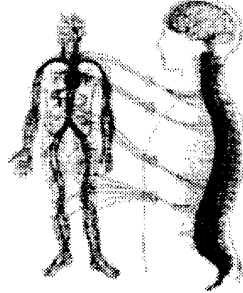(b)

Comparison of CFD and EXP-based, time-varying muscle-mass-specific powers

(a) Inertial powers

(a)

Aerodynamic powers

(b)

Size effect on Near-and far field Flows

Wing span: R

10 cm

10^0 cm

10^{-1} cm

Re=10

Re=100~200

Re=1000

Re=6000~7000

Re=Uc/ν

10^1 10^2 10^3 10^4

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Hawkmoth   *Fruitfly*

(a)   (d)   (g)   (j)

Perspective view

Downstroke   *Upstroke*

Top view

Front view

Meet and diverge   No meet but expand

Two-jet lattice downwash wake

Iso-velocity surfaces of v_z = -0.5 in perspective views of (a), (d) and (g), (j); and by velocity contours and vectors in top and front views of (b), (c), (e), (f), and (h), (i), (k), (l), for hawkmoth and fruitfly hovering, respectively. The iso-vorticity surfaces are also visualized to illustrate the relationship between the downwashes and the VTRs.

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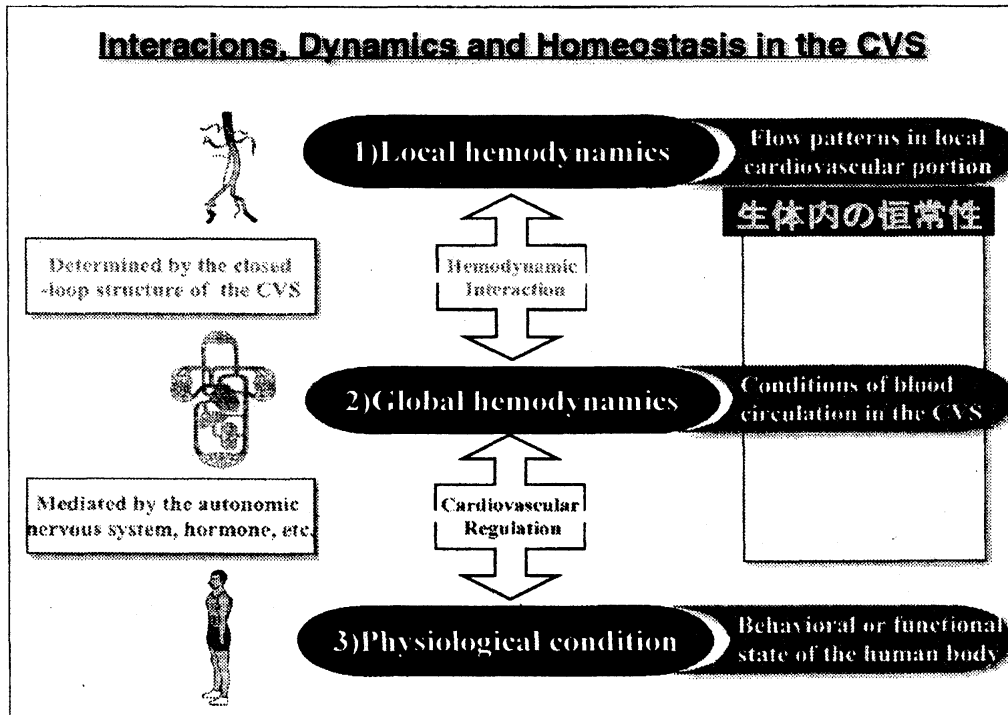
システム的循環シミュレーション
Integrated Simulation of Systems Circulation

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Interacions, Dynamics and Homeostasis in the CVS

1)Local hemodynamics — Flow patterns in local cardiovascular portion

生体内の恒常性

Determined by the closed-loop structure of the CVS

Hemodynamic Interaction

2)Global hemodynamics — Conditions of blood circulation in the CVS

Mediated by the autonomic nervous system, hormone, etc.

Cardiovascular Regulation

3)Physiological condition — Behavioral or functional state of the human body

78

Multi-scale Multi-physics Simulation

循環器フィジオームのプラットフォームの創出

Physiom of Circulatory system

Physiological modeling
Macro
Dynamic regulation

システム循環統合シミュレーション
Integrated Simulation of Systems Circulation

Microcirculation modeling

thermodynamic

An 'alive' CVS modeling for the whole body

Modeling of Red & White cells Micro

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Methodology: A Multi-scale, Multi-physics Simulator of CVS

3D modeling
0D modeling
1D modeling

The aorta and the main large arteries are modeled one-dimensionally.

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A prototype, anatomically realistic arterial-and venous -tree model

A Global Arterial- and Venous-Tree model
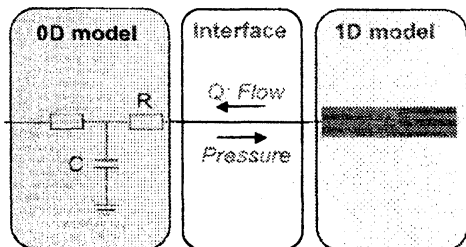A VHP-based prototype model (A:266; V:117)
A CT/MRI-based, individual model
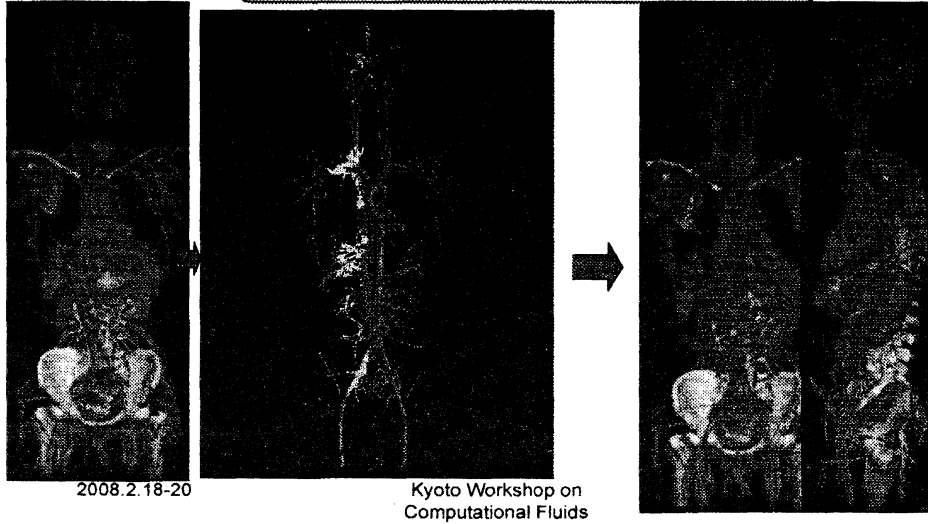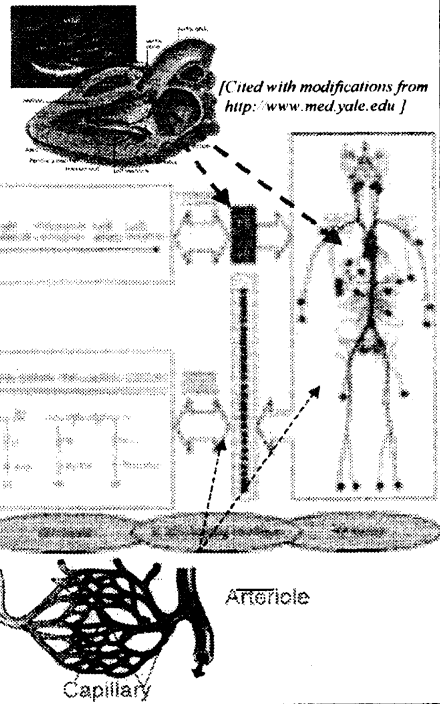

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0-1D coupling methods

[Cited with modifications from
http://www.med.yale.edu]

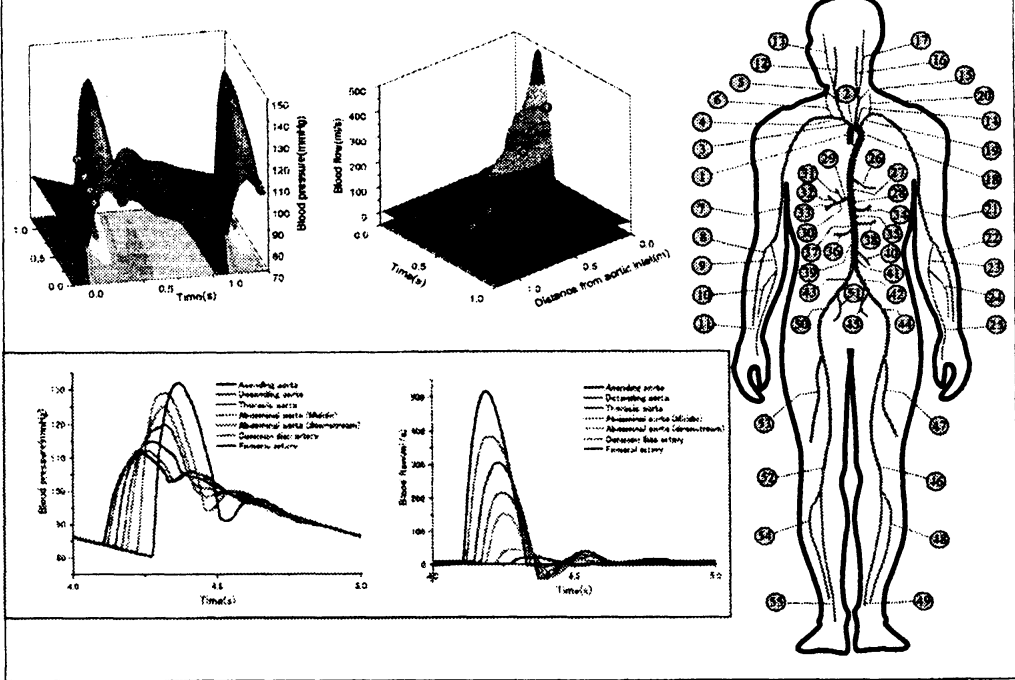0-1D coupling is implemented at the aortic inlet and the distal ends of the large arteries via pressure-flow exchange.

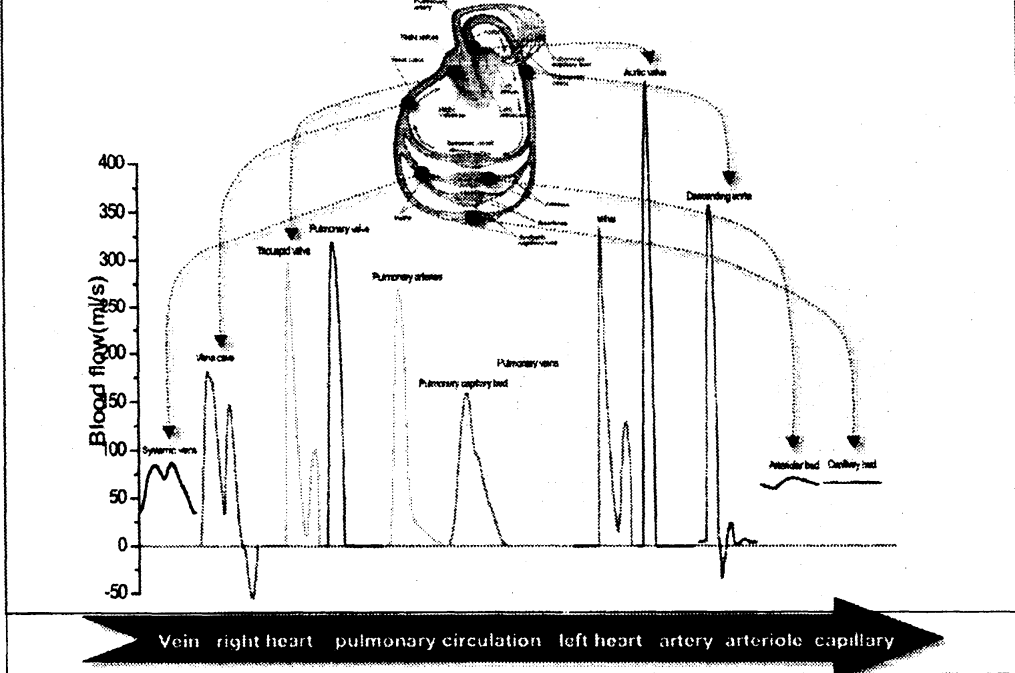| 0D model	Interface	1D model
R C	Q: Flow Pressure	

Venule   Arteriole

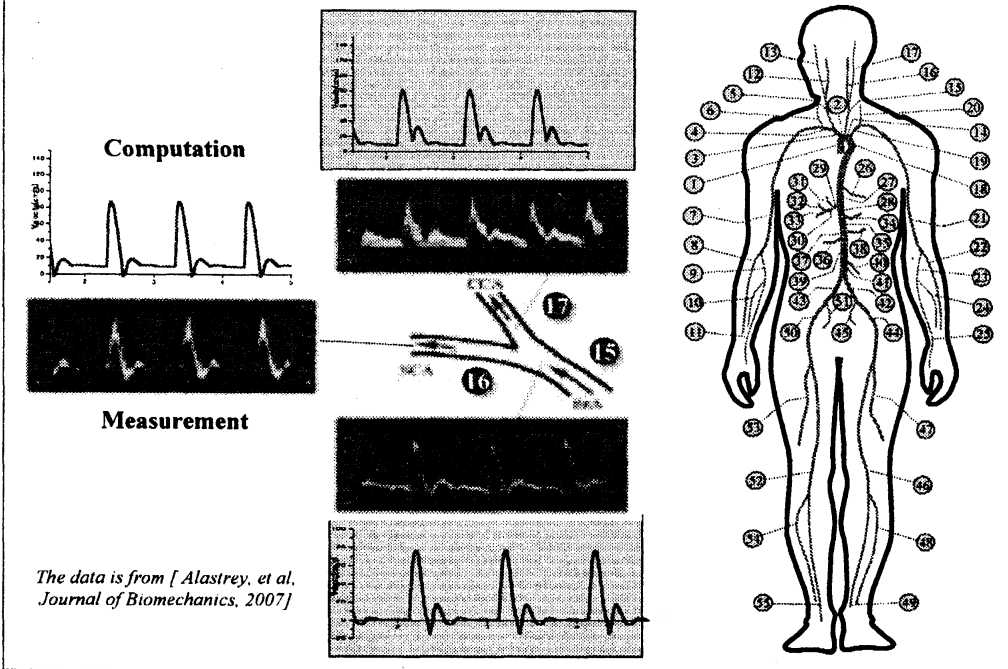2008.2.18-20   Kyoto Worksh
Computational   Capillary

Blood pressure/flow waveforms in the arterial tree

Flow waveforms in the whole cardiovascular system

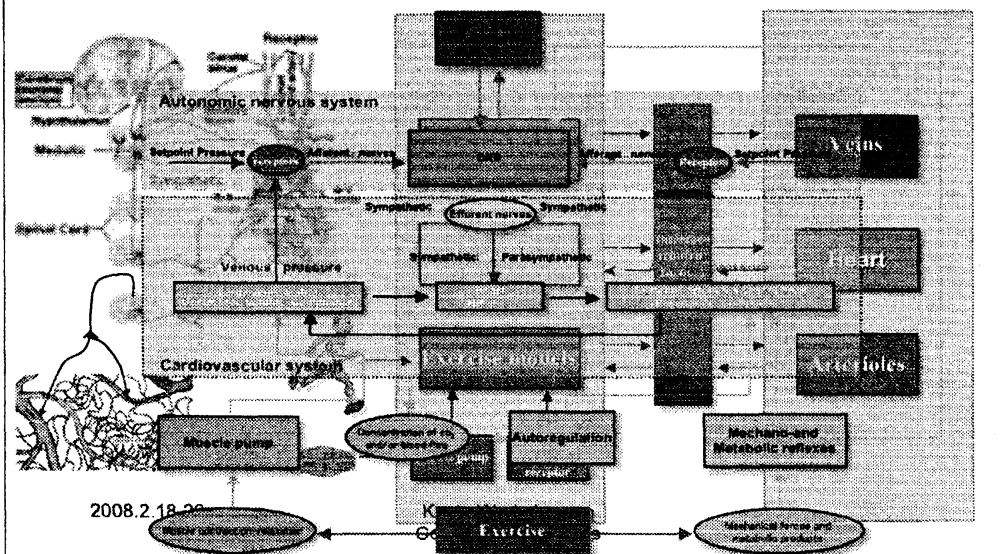## Comparison with physiological data

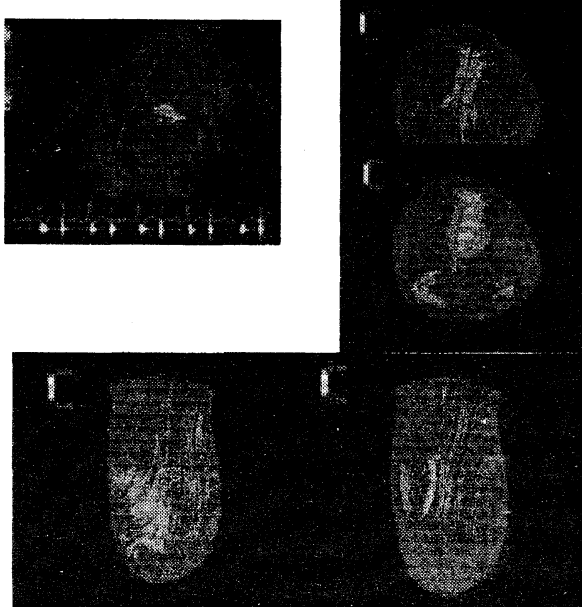
Computation

Measurement

The data is from [Alastrey, et al.
Journal of Biomechanics, 2007]

ANS Modeling

Physiological models and their coupling with 0D model
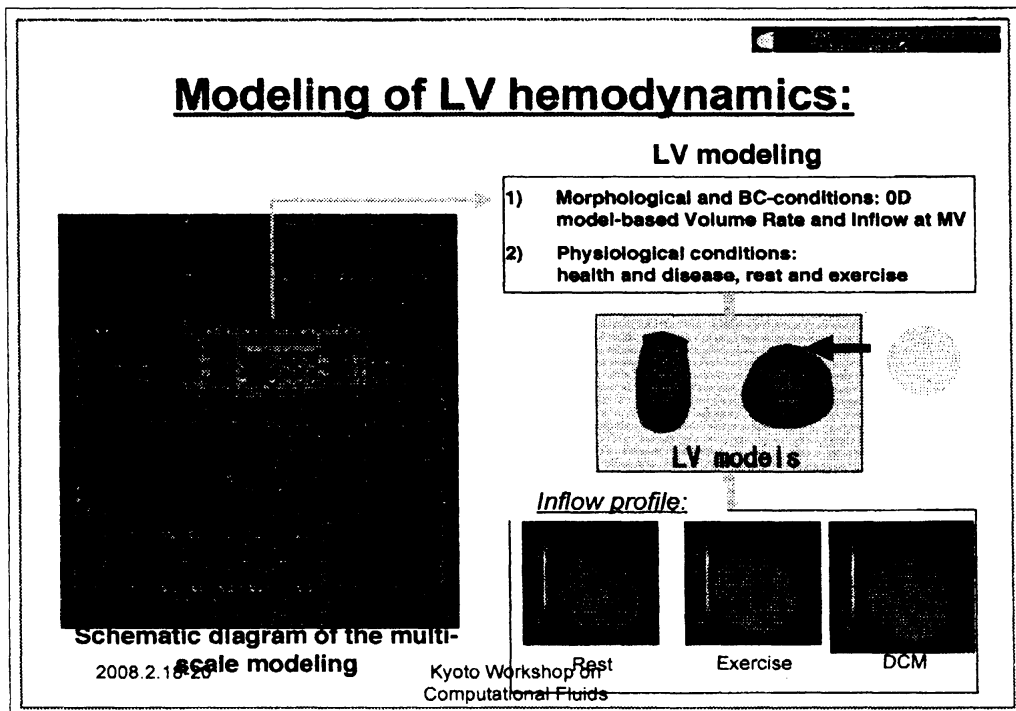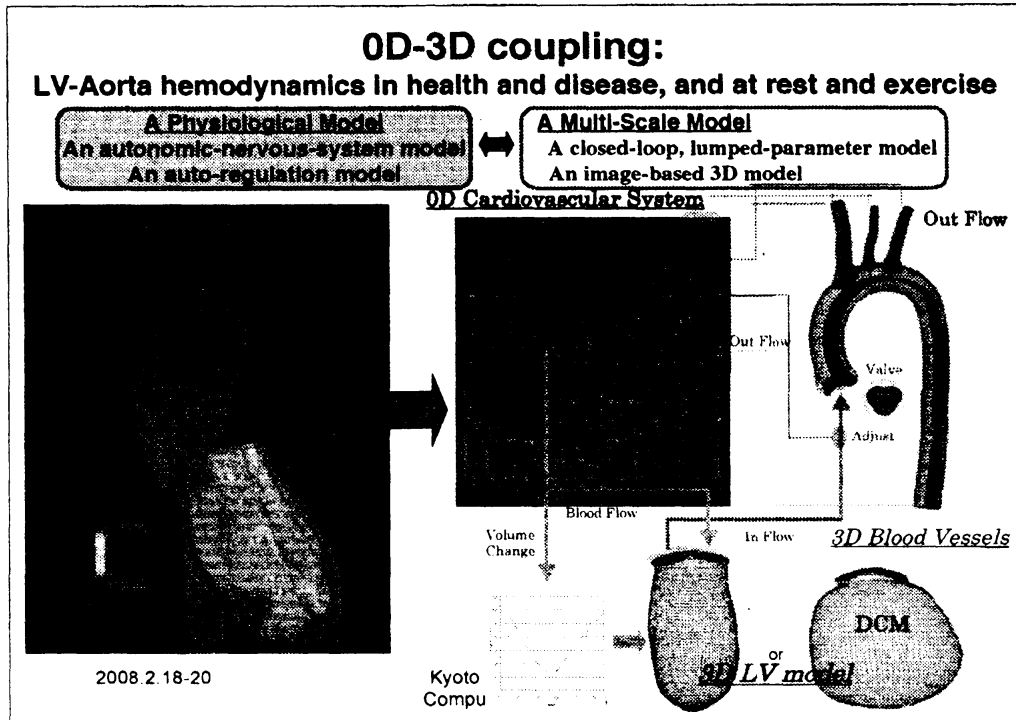
2008.2.18

82

0D-3D coupling:
LV-Aorta hemodynamics in health and disease, and at rest and exercise

Modeling of LV hemodynamics:

83

LV hemodynamics: DCM

The vortex ring in the vicinity of ventricle apex persists almost a whole cardiac cycle, especially the presence of the vortex ring in systole is thought to dissipate the contraction energy of ventricle thus compromising the ventricular pumping function.

Summary:
Enlargement of the ventricle
Spherical transformation of the ventricular shape

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An integrated LV-AA-model:

Rest   Exercise   DCM

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An integrated LV-AA-Multi-Bifurcation model:

下部分岐

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血管壁ずり応力分布

下部分岐

分岐部基部で
高応力

Kyoto Work
Computation

Influence of valsalva sinus

MRA measurement

With sinus   Without sinus

The valsalva sinus seems to stabilize the vortex flow in the Asc. A.

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Influence of valsalva sinus

Measured   **Computed**

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                             Computational Fluids

Future Directions

· **Physically, it should be integrated.**

  Multi-scale and multi-physics over a huge range on an order of 10^9

· **Computationally, it must be large-scale.**

  Parallelization and grid computing

· **In interdisciplinary, it should merge with experiments.**

  **Systematic verification & validation,
  in vivo and *in vitro***

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A universal rule in biological systems:

Local Worse, Global Best!
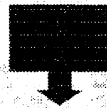
Toward 'Computational' System Biomechanics

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Computational Fluids