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Module 4 - Technology led advancements and innovations in healthcare

Simulation ,organ modelling

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Simulation, Organ Modelling Case Studies

Coronary Artery Blood Flow Simulation & Mathematical Modelling of Human Thermoregulation

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Learning Objectives

After completing this module, the participants will be able to:

1. Understand the basic principles associated with computational fluid mechanics, CFD
2. Analyse fluid mechanics models currently used for clinical research problems,
3. Integrate fluid dynamics engineering concepts to examine and to model the blood flow in human arteries
4. Identify specific diseases and how they are related to fluid dynamics,
5. Have the capability to understand the mathematical human thermoregulation models

Overview

The combination of modeling and medical diagnosis techniques improve the prediction capabilities of the prognosis of diseases and are gaining researcher's attention over the last few decades. Due to the complexity of physiological systems, development of accurate models is quite difficult, challenging, and often not possible. However these models have helped in developing new and improved devices and system designs. Excellent creative models for simulating complex processes in the human body and therapeutic models are now being developed by collaborations between engineers and clinical and medical scientists. This module addresses two case studies describing the use of computational fluid dynamics (CFD) and mathematical techniques: (i) a fully coupled fluid structure interaction (FSI) analysis of pulsatile blood flow through a complaint stenotic artery, and (ii) a multi-segmented human thermoregulation model. Basics of the proposed models are described starting from the fundamental governing equations and highlighting various aspects of the modelling concept. It is expected that the module will help in understanding the basic principles associated with modelling. Descriptions about the errors that occur during computations are also highlighted so that the user can analyse and make critical judgments about the model predictions. With decreasing hardware costs and rapid computing times, researchers and medical scientists may increasingly use these tools to deliver accurate, reliable results.

1 Introduction

The field of applied mathematical modelling of biological systems has developed tremendously during the last decade and continues to develop. The major reason for this development is the ability of these models in obtaining the data with much better resolution in time and space compared to modern invasive and non-invasive measurements. In addition, mathematical modeling of the dynamics can provide new insights into physiological mechanisms. The models will give not only qualitative but also quantitative information of the function they predict and they may also be used to suggest new experiments. Therefore such models are necessary for improving the understanding of the human physiology, and in the long term may help in generating new physiological theories. Some examples are: electrophysiological cellular models [1], modelling cancer in microfluidic human organs [2], models

for gas exchange in the human lungs [3], computational model for Blood flow in the human ascending aorta [4] etc. All these models will provide more insight for structuring thoughts. "For example, when a vein is occluded during surgery, the resistance to the blood flow is increased and as a result a fall in cardiac output is usually observed. However, even though cardiac output usually falls there are cases that show the opposite response: an increase in cardiac output" [5]. The inconsistent responses was better explained using the topology of the cardiovascular system model: increase is noted when the occlusion is in the supply to a highly compliant organ while decrease is noted when supply is to regions of low compliance. An exponential increase in the use of these models can be seen in the medical industry where engineering has a big role. The development of training simulators for the doctors, nurses, and technical personnel will be another area where these models play a big role in future.

Modelling aspects associated with two cases are discussed in detail in this module; (i) blood flow simulations in the coronary arteries, and (ii) mathematical modelling of human thermoregulation. Computational fluid mechanics is used to simulate blood flow in stenosed arteries for the reconstruction of wall shear stress and to shape medical treatment. The study can very well give insights to the role of hemodynamics on atherosclerosis initiation and progression. This is addressed by many researches as the coronary heart diseases is one of the leading causes of morbidity and mortality globally [6]. Since 1960s, various thermoregulation mathematical models have been developed, (i) to enhance our understanding of the principles of human thermoregulation, (ii) to design devices for thermal therapies, and (iii) to increase tolerance limits, thermal acceptability and energy efficiency under exposure to hostile environments such as fire fighting, manned missions and extra-vehicular activities (EVAs) etc. One of the most influential models that paved the foundation of this area of research was developed by Stolwijk [7] for NASA to predict thermal responses of astronauts during their activities in space outside the spacecraft. Details of the model are described in the following sections.

2 Coronary artery blood flow simulation using CFD

Computational fluid dynamics (CFD) is a very powerful technique for analyzing fluid flow, heat transfer, and associated phenomena with the use of computer-based simulation. CFD was initially limited to high-technology engineering areas, but now has become is a widely adopted technique for solving complex problems in many diverse fields including biomedical engineering. The complexity of human anatomy and human body fluid behaviour has created lot of challenges to CFD research in the biomedical field. However, the technique is more accessible now due to high performance hardware and software availability. Through the use of this technique, medical researchers have gained more knowledge of body fluids and components and are able to make improvements for biofluid physiology studies, and to develop medical devices. CFD will provide an opportunity to simulate the conditions before real commitment and therefore provide improvements in design and direction in medical interventions.

2.1 Short description about the method

The fundamental laws of mechanics give the following governing equations for a fluid: The conservation of mass equation and momentum equations are

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla . \rho \vec{V} &= 0 \\ \rho \frac{\partial \vec{V}}{\partial t} + \rho (\vec{V} . \nabla) \vec{V} &= \nabla p + \rho \vec{g} + \nabla . \tau_{i.j} \end{aligned} \tag{1}$$

where ρ, $\vec{V}$, t, p, and τ corresponds to density, velocity, time, pressure and shear stress respectively. Along with energy equation, this will for a set of coupled, nonlinear partial differential equations. These equations are valid for the continuous domain, such that each flow variable is defined at every point in the domain. It is not possible to solve these equations analytically for most engineering problems. Therefore approximate solutions are obtained based computer based methods. The strategy is to replace the continuous problem domain with a discrete domain using a grid with each flow variable is defined only at the grid points. Figure 1 illustrates the two aspects. The governing partial differential equations and boundary conditions are approximated in the discrete domain in terms of the

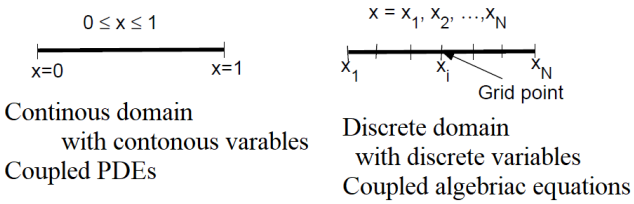

Figure 1: Illustration of continuous and discrete domain for an 1D system

discrete variables. The discrete system is a large set of coupled, algebraic equations in the discrete variables. Solution of this discrete system involves a very large number of repetitive calculations, which is usually performed using computer. An example of discreitization using the Finite-Difference Method is explained below. Consider a simple 1D equation in continuous domain such as

$$\frac{\partial u}{\partial x} + u = 0; \quad 0 \leq x \leq 1; \quad u(0) = 1 \tag{2}$$

A discrete representation of the system with four equally spaced grid points is shown figure 2 Since

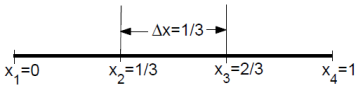

Figure 2: A discrete representation with four equally spaced grid points for an 1D domain

the governing equation is valid at any grid point, the equation for every point is

$$(\frac{\partial u}{\partial x})_i + u_i = 0; \quad where \;\; i = 1, 2, 3, 4 \;\; represents \;\; the \;\; grid \;\; points. \tag{3}$$

Now for every grid pint, $\frac{\partial u}{\partial x}$ is approximated as an algebraic equation using Taylor's series as given below.

$$(\frac{\partial u}{\partial x})_i = \frac{u_{i-u_{i-1}}}{\Delta x} + Truncation \; error \tag{4}$$

Now excluding the error, the governing equation becomes

$$\frac{u_{i-u_{i-1}}}{\Delta x} + u_i = 0 \tag{5}$$

Note that the differential equation is converted to an algebraic equation. This method of deriving the discrete equation using Taylor's series expansions is called the finite-difference method. However, most commercial CFD codes use the finite-volume or finite-element methods which are better suited for modeling flow past complex geometries. The equations generated at every grid point can form a system of four simultaneous algebraic equations in the four unknowns u_1, u_2, u_3 and u_4. The four algebraic equations will be

$$-u_1 + (1 + \Delta x)u_2 = 0; \quad -u_2 + (1 + \Delta x)u_3 = 0; \quad -u_3 + (1 + \Delta x)u_4 = 0; \quad -u_1 = 1 \tag{6}$$

Thus a system of simultaneous algebraic equations is obtained with the number of equations being equal to the number of independent discrete variables. In a general situation, one would apply the discrete equations to the grid points (or cells in the finite-volume method) in the interior of the domain. For grid points (or cells) at or near the boundary, one would apply a combination of the discrete equations and boundary conditions. An iterative procedure is used to find the four unknowns u_1, u_2, u_3 and u_4. the longer one iterates, the closer one gets to the true solution. The iterations will be terminated when the residual falls below the convergence criterion. The convergence criterion for each conservation equation is problem and code dependent. In complex problems, the

iterations converge slowly and in some instances, may even diverge. The condition under which a given numerical scheme converges is determined by performing a stability analysis of the numerical scheme. A numerical method is referred to as being stable when the iterative process converges and as being unstable when it diverges. The nonlinearity of the governing equations, and the additional nonlinearities associated with phenomena such as turbulence and chemical reaction for a fluid makes it challenging to obtain accurate numerical solutions for complex flows of practical interest.

2.2 CFD for human cardiac vasculature

Computational flow simulation along with medical imaging can provide valuable information on the hemodynamic effects and anatomic alterations of the arteries due to the presence of stenosis which is accompanied by thrombus formation, atherosclerosis growth, and plaque cap rupture. Stenosis can induce significant pressure drops, increases wall shear stress (WSS)/wall motion, flow separation and plaque rupture. [8], [9]. It is reported that atherosclerosis is globally the leading cause of disability and death in the developing world [10]. Prevention of Coronary heart disease (CHD) and other manifestations of atherosclerosis are important as its occurrence and economic burden are likely to shoot up in the coming years [11]. Low and oscillatory WSS and changes in haemodynamics are identified as the most important determinant in atherosclerotic disease[12]. Endothelial cells process WSS changes and triggers and modulates adaptation and remodelling which in turn alters flow behaviour and WSS. CFD enabled parameters such as local pressure gradient, wall shear stress and flow velocity changes downstream of the plaque can be used for early detection and prediction of coronary artery disease [13]. Large number of numerical simulations can be seen in literature discussing cartoid artery [14], [15],[16] , left coronary artery [17],[18] and its bifurcations to the left anterior descending (LAD)and left circumflex (LCX) arteries [19]. However accuracy of these predictions depends on the accuracy of the computational domain, modelling of blood properties and the boundary conditions imposed.

2.3 A case study

Methodology adopted for a numerical study of haemodynamics behaviour in normal and single stenosed artery using Fluid – Structure Interaction is described here. This is based on the study conducted by Basri et al.[20]. A 3D model of an idealistic abdominal aorta with renal branches with the normal and single stenosed cases was investigated. 3D abdominal aorta model was generated using single slice technique base on Computed Tomography (CT) image. CT image and the constructed idealised geometry are shown in figure 3. The fluid domain consisted of the blood path and the arterial wall forms the solid domain. Both the domains are discretised using 85000 and 55000 hexahedral elements. These optimum grid sizes were selected after a grid independence study. This is done to eliminate the influence of number of grids/grid size on the computational results. The boundary conditions for the fluid domain inlet and outlet were time varying pulsatile periodic velocity and pressure as shown in figure 3. The governing equations for the fluid domain were the unsteady mass and momentum equations. Blood was assumed as Newtonian and incompressible. Artery wall was assumed to be linearly elastic, isotropic, incompressible and homogeneous. Two-way sequentially coupled transient FSI analysis was performed using a commercial CFD software ANSYS [21]. Ansys Fluent was used for the fluid domain simulation and the pressure loads from this was transferred to the solid domain through an interface. Solid domain is solved by the ANSYS Mechanical Solver. The haemodynamics parameters such as velocity, pressure, WSS, arterial wall deformation etc obtained from the model at specific instants of pulse cycle like early systole (ES), peak systole (PS), early diastole (ED) and late diastole (LD).

Current research indicate that various imaging techniques such as computed tomography, MRI and ultrasound imaging can be used to obtain more accurate and detailed geometry. Some of the important studies are the following. Ramaswamy et al.[22] used angiography and Intravascular ultrasound (IVUS)data from a patient undergoing catheterization to reconstruct the LAD coronary artery for the simulations and studied the arterial motion effects on blood flow patterns. Torri et al. [23] obtained multi-slice computerized tomography (CT) images of a patient with mild stenosis and created cross-sectional outline data of perpendicular planes of 1 mm intervals related to right coronary artery. Magnetic resonance angiograms (MRA) extracted from from the multisequence MRI of six patients with different degrees of stenosis and two healthy volunteers were used by Mendieta et al. [24] to

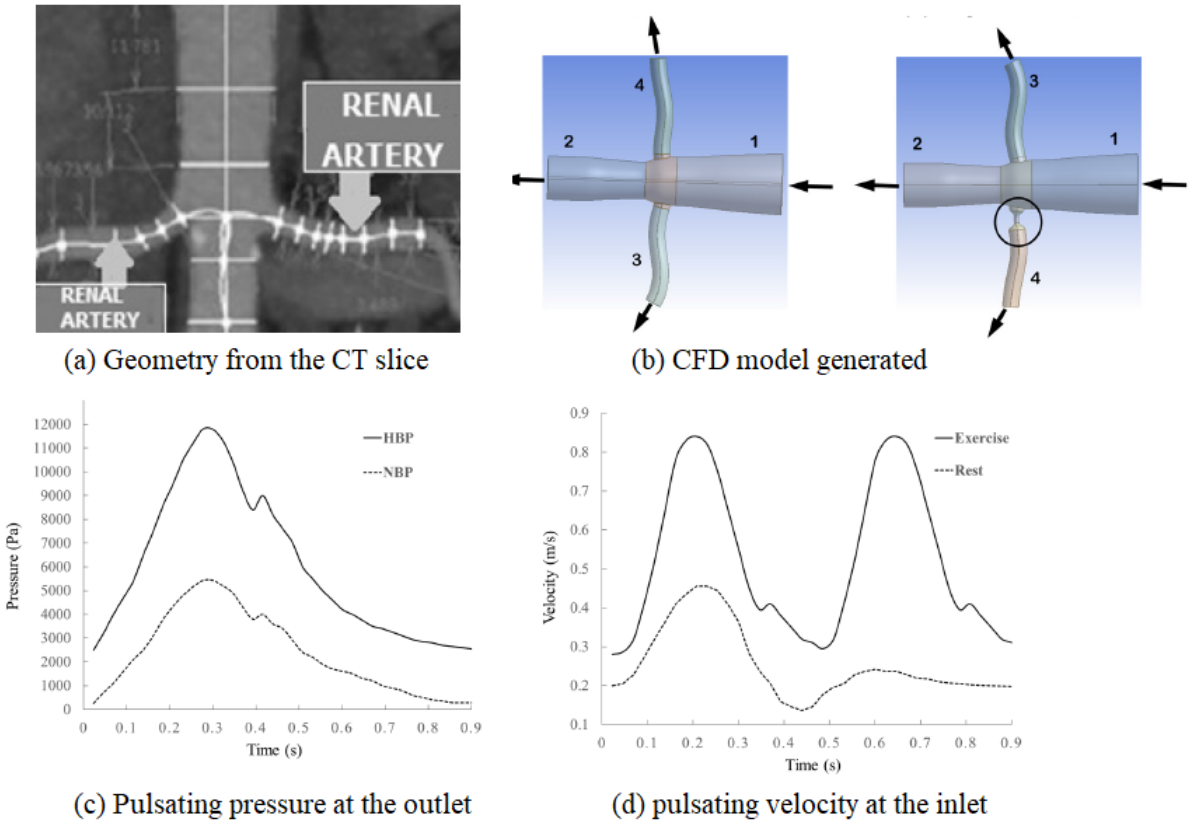

Figure 3: Details of the computational model [20]

study the differences in pressure gradient and wall shear stress descriptors between various blood viscosity models. CT volume data of a patients having healthy and coronary artery disease was used by Kamangar et al.[25] to study hyperemic flow condition using CFD. Techniques like MRI, Doppler ultrasound, pressure wire, and other non-invasive techniques will provide flow conditions of the arterial network at specific time of specific case. Various studies have implemented such data for the boundary conditions for the domain selected. Researchers [26], [27] have established that blood behaves as Newtonian at higher ($> 100s^{-1}$) shear rates. However, during cardiac cycle, there are periods when the shear rates are less than this limit and non-Newtonian effects become more prevalent [26]. Major reputable non Newtonian models used to describe rheology of blood flow in arteries include Casson, K-L, Modified Casson, Carreau, Carreau-Yasuda, Cross, Power-law, Modified Power-law, and Generelized Power-law models [28].

3 Modelling of human thermal regulation

In the past, various analytical thermal regulation models had been developed to simulate thermal response of humans. These models have been used in supporting physiological experiments as well as to analyse human interactions with a variety of environments such as space travel [29], aeroplanes [30], vehicles [31], buildings [32] etc. Thermal regulation models developed for predicting the skin temperatures involve passive and active systems of the body [33]. The passive system mainly depends on the individual characteristics of the body such as height, mass, body surface area, and fat percentage. The various aspects of thermal regulation viz, core body temperature, heat transfer mechanisms, modeling aspects along with passive and active system description, and potential applications of these models are described in detail below.

3.1 Body heat exchange mechanism

The concept of normal core body temperature of approximately 37°C goes back to 19^{th} century. The credit of early research goes to Wunderlich [34] who is believed to have proposed the data supervising approximately 25000 patients. Modern researchers [35] have also observed similar temperature, though mean temperatures are lower than that of Wunderlich. The heat gains of the human body include heat production due to metabolic activity, or heat gain through radiation and conduction from environment through skin. Basic metabolic rate for a typical human being is around 100 W out of which around 15% is produced by the brain. During high mental activity this can be even higher, which demands specialized thermoregulatory physiology. Major heat losses are through conduction, convection, radiation, evaporation and respiration. The sensible heat loss is around 75% whereas evaporation contributes to 25% [36]. Contribution from convection and radiation are almost equal during normal indoor environments with still air [37]. Since evaporation is a highly efficient heat removal process, body utilises this mechanism effectively under high thermal stress conditions. Eccrine glands secrete sweat on to the surface of the skin based on the sweat command and the sweat gets evaporated by the heated skin surface. These glands are regulated by the nervous system, which releases the neurotransmitter acetylcholine. Rate of sweating is increased initially by increasing the amount of sweat from each gland [38] and then increasing the participating glands. The sweat sequence is usually followed in order by upper arms, hands, feet and back and abdomen [39]. Convection and radiation heat exchange from the body are controlled by varying the skin temperature. This is done by changing the blood circulation near the skin; reducing the blood circulation (vasoconstriction) or enhancing the circulation (vasodilatation). This is achieved by vasoconstriction or vasodilatation of venous plexus, a dense vascular network below the skin. The blood vessel diameter changes significantly and affects the supply volume of blood, resulting significant changes in the local temperature gradient across the skin. Dilatation will result in increase of skin conductance whereas constriction will reduce it. Stimulation of these activities takes place through the sympathetic nervous system. In addition to the above mechanism, Arterio-venous anastamoses (AVA) [40] will open and shortcut the blood flow from the arterioles to the venous plexus during hot environmental conditions. This will allow the warm blood from the arterioles to flood in the venous plexus, which in turn promotes conduction through overlying tissues. In addition to the above mechanisms, the counter current heat exchange between arteries and veins will also play major role in keeping the body temperature constant.

3.2 Thermoregulation models available in literature

Various human thermoregulatory models are available in literature to assess the thermal response for a range of environmental conditions. These models incorporated anatomic representation of the body and the physiological responses through a passive and active system approach. One of the simplest model proposed is that of Gagge et al. [41]. He proposed a two-node model with regulatory commands expressed as a function of core and skin temperatures. The basic concepts, algorithms, and control aspects of majority of the muti-node models available in literature were provided by Stolwijk [7]. UC Berkeley [42] developed a comprehensive model with the capability to include unlimited number of segments along with a unique counter-current heat exchange model for blood flow. This model has the capability to predict thermal response under transient and complex radiative environments and is considered to be a milestone in the human thermoregulation model development [43]. The notable extensions from the fundamental Stolwijk's model were Fiala et al.,[44], Tanabe and Kobayashi model [45], and Salloum et al. (AUB model)[46]. The AUB model used accurate anatomical data and calculated blood perfusion in the tissue based on the heart rate input. However, this model had the limitation in using in non-uniform environmental conditions [47]. Other examples of multi-node models include Fiala et al. [48], Kingman et al. [49], Novieto [50], Lai and Chen [51] etc. Another category of models developed are multi-element models which simulate human body as various body parts without further dividing it into nodes similar to multi-node models as seen in Ferreira and Yangihara, [52], Sun et al. [53], Tang et al.[54] etc. However it can be noticed that all the recent and advanced models are improvements and modifications of the fundamental Stolwijk model [7].

3.3 Stolwijk model

This model consists of two interacting systems – active and passive. The human body is divided into segments and sub-segments made up of simple geometries like sphere and cylinders. The body compartmented into 6 segments of sphere and cylinders and all these segments are linked to a central blood compartment. These segments each are further divided into 4 concentric layers each of core, muscle, fat, and skin. These nodes will have conduction heat transfer between them, convection heat transfer with blood; participate in various thermoregulation mechanisms and environmental interaction as shown in figure 4. This constituted the passive system which senses the external conditions and sends the input signals to the active system. The passive system is defined in terms of its mass, surface area and thermal conductance which are calculated based on the physical characteristics and thermophysical properties. Phenomenon like conduction, convection, radiation, evaporation, and res-

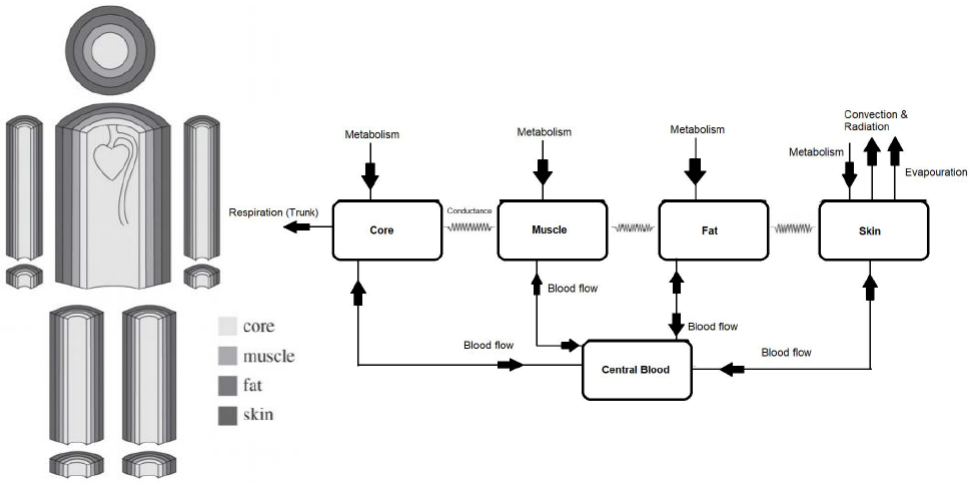

Figure 4: Details of each segment showing various nodes and its interactions system, [55]

piration occurs in the human body, thermal conduction takes place between connecting layers and the convection takes place between layer and the central blood compartment. Respiration occurs through trunk core. Evaporation, convection, and radiation occur on the skin layer. Each layer is a lumped capacitance and has its metabolic heat production. The heat balance of nodes of each segment is described as follows.

$$
\begin{aligned}
\text{Core layer}: \quad & C_{i,1}\frac{\mathrm{d}T_{i,1}}{\mathrm{d}t} = Q_{i,1} - BC_{i,1} - TD_{i,1} - \mathrm{E}_{i,1} \\
\text{Muscle layer}: \quad & C_{i,2}\frac{\mathrm{d}T_{i,2}}{\mathrm{d}t} = Q_{i,2} - BC_{i,2} + TD_{i,1} - TD_{i,2} \\
\text{Fat layer}: \quad & C_{i,3}\frac{\mathrm{d}T_{i,3}}{\mathrm{d}t} = Q_{i,3} - BC_{i,3} + TD_{i,2} - TD_{i,3} \\
\text{Skin layer}: \quad & C_{i,4}\frac{\mathrm{d}T_{i,4}}{\mathrm{d}t} = Q_{i,4} - BC_{i,4} + TD_{i,3} - TD_{i,4} - E_{i,4} \\
\text{Cloth layer}: \quad & C_{i,5}\frac{\mathrm{d}T_{i,5}}{\mathrm{d}t} = TD_{i,4} + E_{i,4} - (HC(i)(T_{i,5} - T_{air}) + \sigma\epsilon(T_{i,5}^4 - T_{sur}^4))S(i)
\end{aligned}
\tag{7}
$$

where i represents body segments, j (1 to 6) represents the different layers of core, muscle, fat, skin and cloth layers respectively. The heat balance of the central blood compartment is given by

$$
\text{Central blood}: \quad C_{\mathrm{b}}\frac{\mathrm{d}T_{\mathrm{b}}}{\mathrm{d}t} = \sum_{i=1}^{6}\sum_{j=1}^{5} BC_{i,j} \tag{8}
$$

A disturbance in environmental conditions or metabolism resulted a change in the controlled variables of the feedback control system (active system). Thermal receptors present in the body measured these changes and generated neural or hormonal information. This feedback along with reference generated the error signal which activates the control centre and corresponding control action. The error signal

generated is

$$ERROR(\mathrm{N}) = \mathrm{T(N)} - \mathrm{TSET(N)} + \mathrm{RATE(N)}^{*}\mathrm{F(N)} \quad (9)$$

where T is the instantaneous temperature of the compartment, $RATE$ is the dynamic sensitivity of the thermoreceptors. F is the rate of change of temperature. T and F are computed at every iteration from the passive system whereas $TSET$ and $RATE$ are constants initially provided to the model. The effector actions - Blood flow rate, evapourative heat loss and metabolic heat production for each compartment are estimated for each segment and its layers. The active system generates thermoregulatory commands to regulate the body temperature based on the error signal generated. The thermoregulatory commands being shivering, sweating, vasodilation and vasoconstriction. These commands are estimated as described in in Stolwijk [7] and Konz et al.[56]. The model is simulated by implementing an algorithm in a numerical computing environment. Figure 5 shows the flowchart of the program developed. The input data consists of (i) geometrical inputs such as the surface

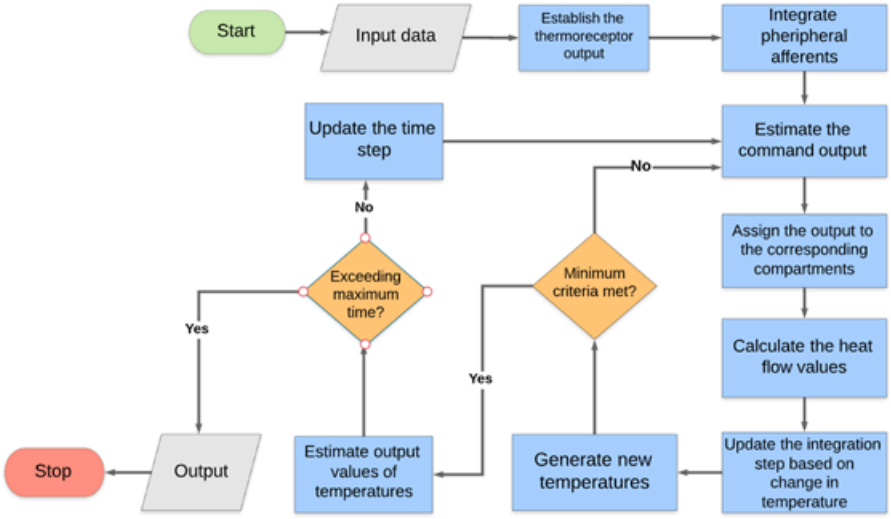

Figure 5: Flow chart showing the algorithm

area of the segments, capacitance ($m \times c_p$), (ii) environmental condition inputs such as ambient temperature, humidity, vapour pressure, air velocity, convective & radiative heat transfer coefficients, (iii) physiological inputs such as basal metabolic, evaporative and blood flow rates, etc., and (iv) temperature inputs such as initial temperature and the reference temperature. The major output from the model is the body temperature though other variables such as evaporation rate, sweat rates, sweat/shiver command etc. can also be obtained as output. A schematic diagram of the thermophysiological models showing the passive and active system interaction is shown in figure 6.

3.4 Applications of thermoregulation models

- As a thermal analysis tool for support of the development of the Space Suit System (SSS).
- To predict the human thermal response to the space flight environment.
- In the development of UTCI. The UTCI equivalent temperature presents the air temperature of the reference environment that gives the same strain index.
- Medical applications. E,g. A model was developed at Maastricht University and Eindhoven University of Technology for predicting response of patients during open heart surgery [58].
- For various thermal suit designs, cloth designs etc. Development of sweating manikins for measuring thermophysical properties of different clothing, sleeping bags, mattresses etc. uses thermophysical models.

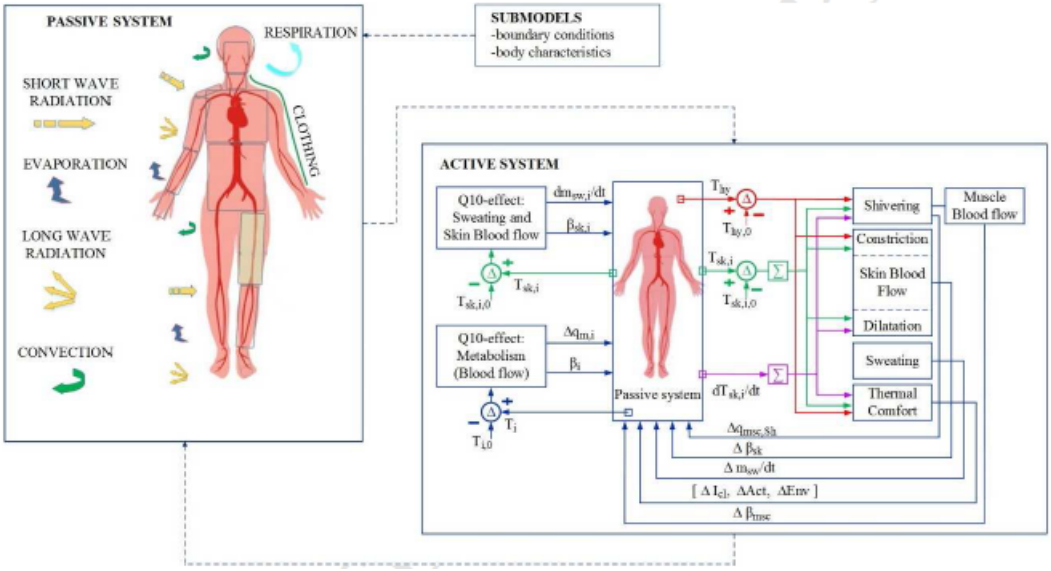

Figure 6: Schematic diagram of the thermophysiological models, [57]

- Design of sports stadiums. Fiala model was used to design sports stadiums [59]. E.g. Stadium Astralia used for 2000 Olympics. The thermophysical model was used for predicting thermal stress on spectators under various roof designs.
- Improving thermal comfort car cabins. Models are used to predict thermal responses of humans in the car cabin.

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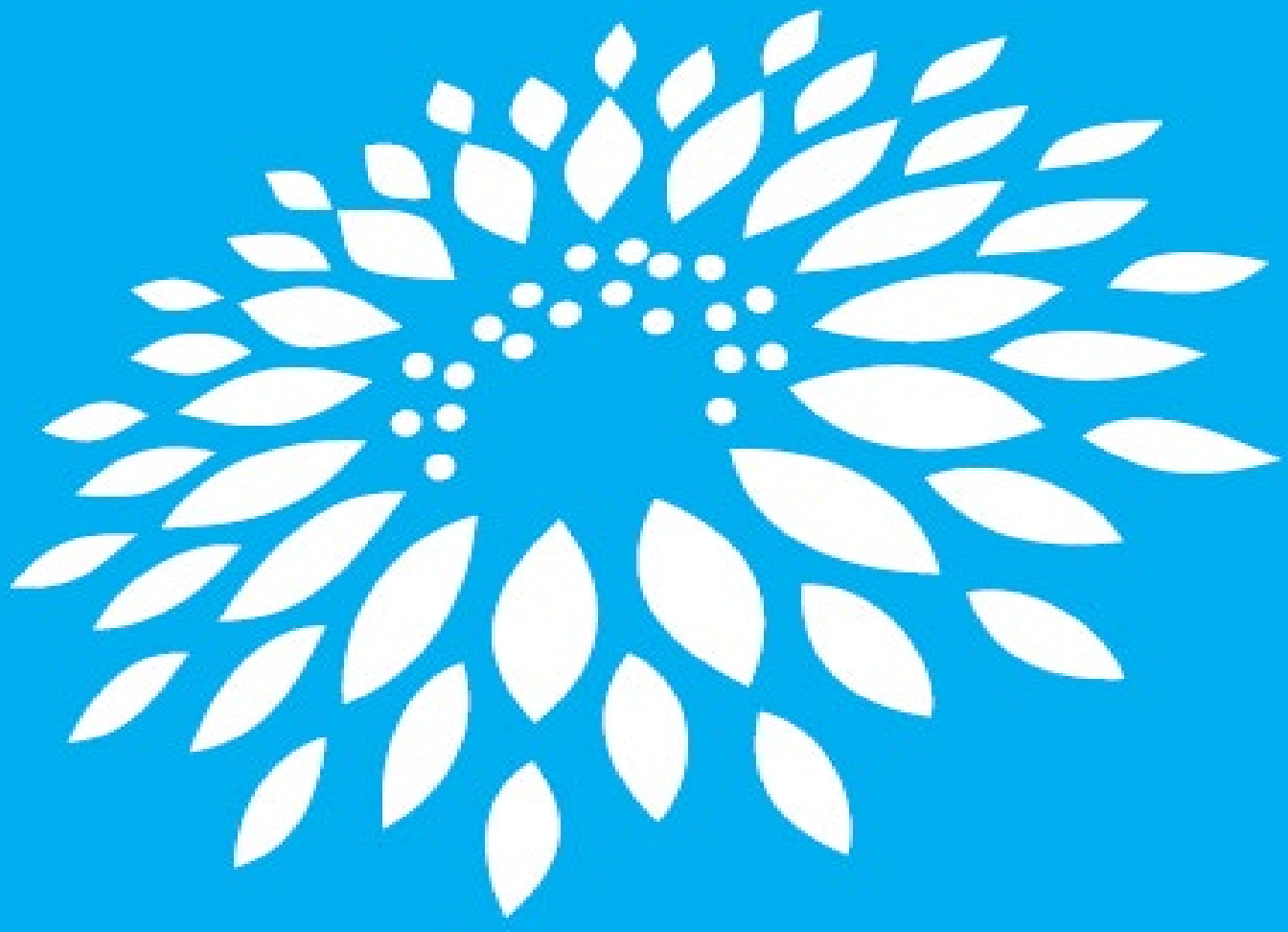
Presentations



Certificate Course in Healthcare Technology

Simulation, Organ Modelling Case Studies

Coronary Artery Blood Flow Simulation & Mathematical Modelling of Human Thermoregulation

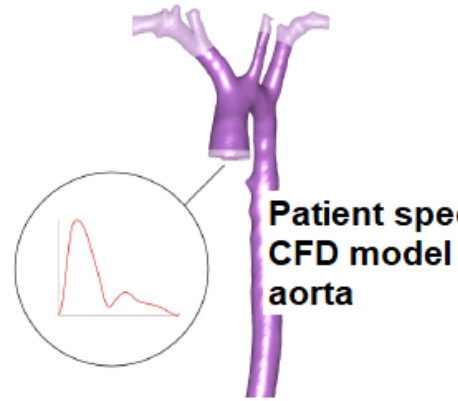
Shine S R, Ph D

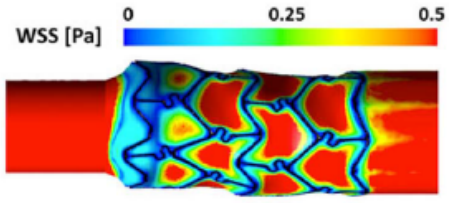
Department of Aerospace Engineering

IIST Thiruvananthapuram

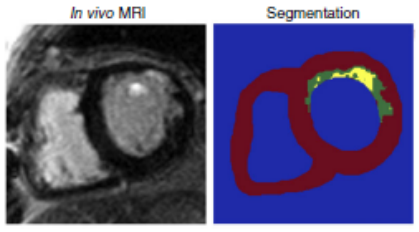
Introduction

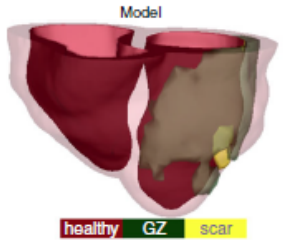
1. Modelling facilitates rapid, economical, and low-risk prototyping.
2. Enables detailed characterisation of complex physiological pressure and flow fields which cannot be directly measured.
3. Patient-specific modelling enables individualised risk prediction and virtual treatment planning.
4. Models have potential to reduce the cost, time and risk associated with clinical trials
5. Enhances diagnostic assessment, device design and clinical trials





WSS along arterial wall





Model of arrhythmia from MRI

Introduction- *Why for space travel*

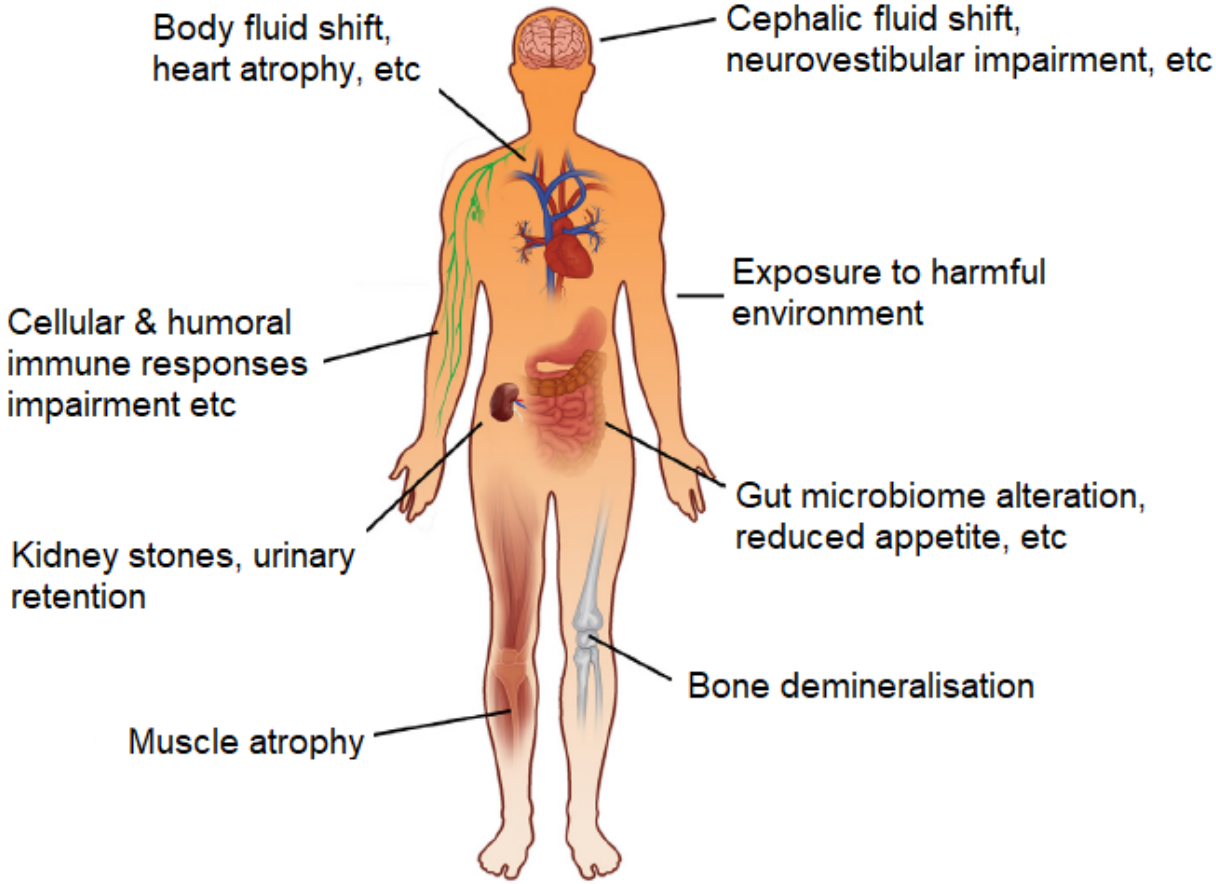


Figure: Main physiological effects of long term exposure to microgravity [1]

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CFD

What is CFD?

- Computer simulation for prediction of fluid-flow phenomena. It includes modeling (mathematical physical problem formulation) and numerical methods (discretization methods, grid generations, etc.)

Why use CFD?

- Simulation-based design instead of build & test; More cost effective and more rapid; high-fidelity database for interrogation of flow field
- Simulation of physical fluid phenomena that are difficult to be measured by experiments; Scale simulations (e.g., full-scale ships, airplanes); Hazards (e.g., explosions, radiation, pollution); Physics (e.g., weather prediction, planetary boundary layer, stellar evolution)
- Knowledge and exploration of flow physics

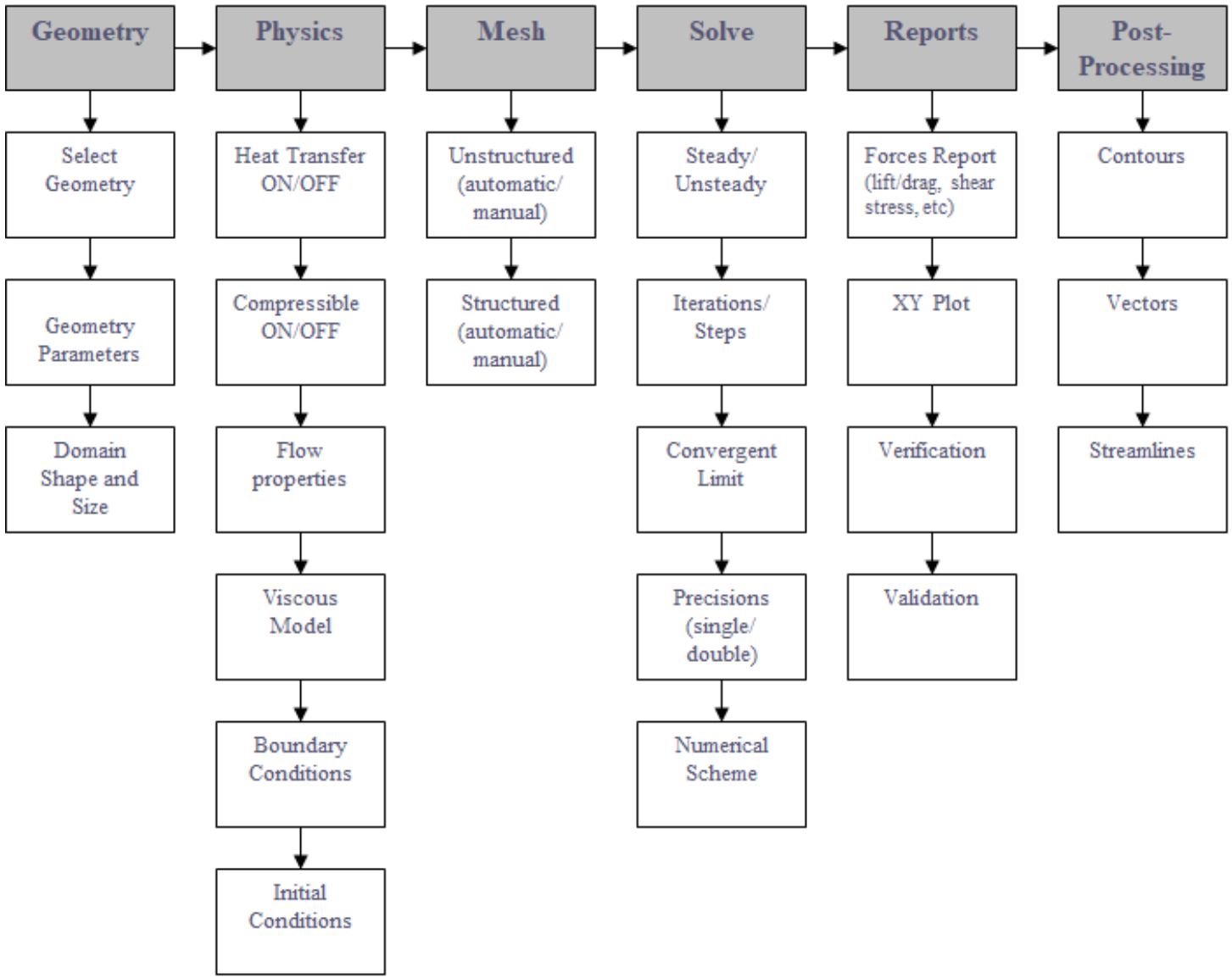
Steps in CFD

- Mathematical representation of the physical problem -Partial Differential Equations (PDEs) with appropriate boundary conditions and initial conditions.
- Discretization into algebraic equations; FDM (straightforward to apply, usually for regular grid) and FVM & FEM (usually for irregular meshes) - numerical methods. Assemble the system of algebraic equations and solve the system to get approximate solutions.
- Numerical methods include:
  1. Discretization methods
  2. Solvers and numerical parameters
  3. Grid generation and transformation
  4. High Performance Computation (HPC) and post-processing

CFD Process

- Geometry description
- Specification of flow conditions and properties
- Selection of models
- Specification of initial and boundary conditions
- Grid generation and transformation
- Specification of numerical parameters
- Flow solution
- Post processing: Analysis, and visualization

CFD process


Geometry
Select Geometry
Geometry Parameters
Domain Shape and Size
Physics
Heat Transfer ON/OFF
Compressible ON/OFF
Flow properties
Viscous Model
Boundary Conditions
Initial Conditions
Mesh
Unstructured (automatic/ manual)
Structured (automatic/ manual)
Solve
Steady/ Unsteady
Iterations/ Steps
Convergent Limit
Precisions (single/ double)
Numerical Scheme
Reports
Forces Report (lift/drag, shear stress, etc)
XY Plot
Verification
Validation
Post-Processing
Contours
Vectors
Streamlines

An example

$$\frac{\partial u}{\partial x} + u = 0; \quad 0 \leq x \leq 1; \quad u(0) = 1 \tag{1}$$

$$(\frac{\partial u}{\partial x})_i + u_i = 0; \quad \textit{where} \quad i = 1, 2, 3, 4 \quad \textit{represents the grid points.} \tag{2}$$

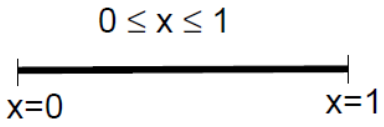
Now for every grid pint, $\frac{\partial u}{\partial x}$ is approximated as an algebraic equation using Taylor's series as given below.

$$(\frac{\partial u}{\partial x})_i = \frac{u_{i-u_{i-1}}}{\Delta x} + \textit{Truncation error} \tag{3}$$

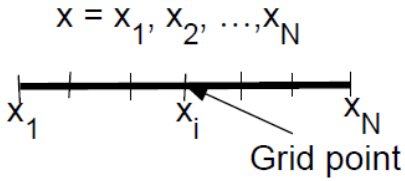
Now excluding the error, the governing equation becomes

$$\frac{u_{i-u_{i-1}}}{\Delta x} + u_i = 0 \tag{4}$$

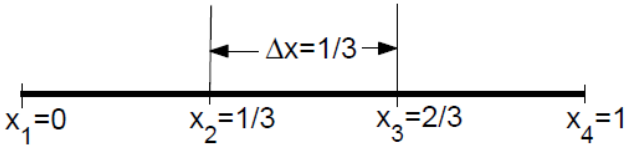
An example



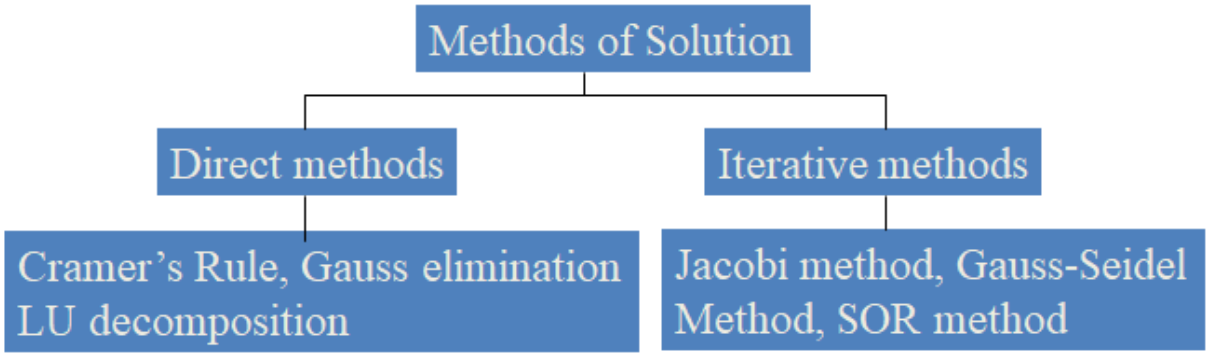
Continous domain
with contonous varables
Coupled PDEs



Discrete domain
with discrete variables
Coupled algebriac equations



$$-u_1 + (1+\Delta x)u_2 = 0; \quad -u_2 + (1+\Delta x)u_3 = 0; \quad -u_3 + (1+\Delta x)u_4 = 0$$

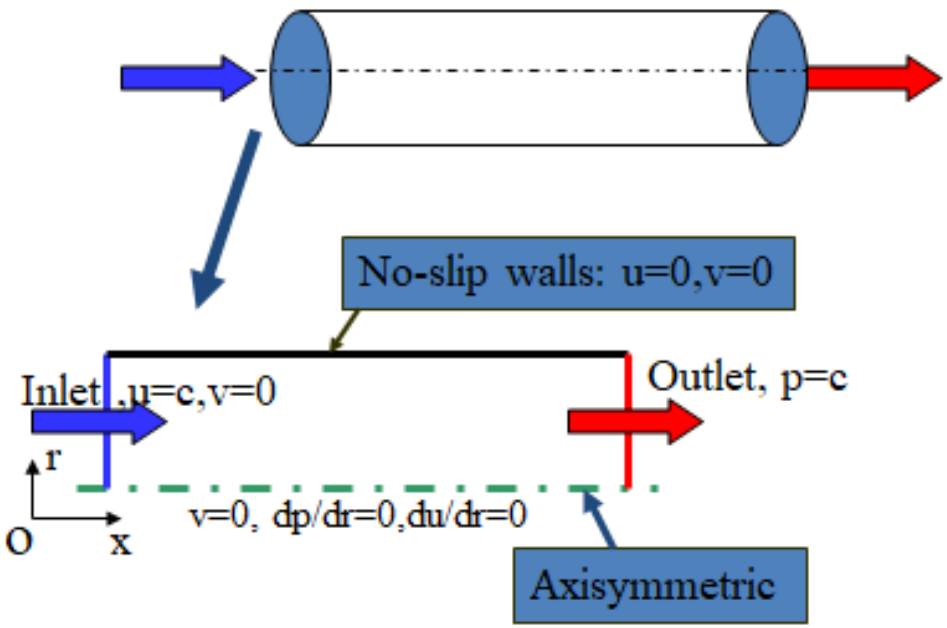


An example

The conservation of mass equation and momentum equations are

$$\frac{\partial \rho}{\partial t} + \nabla . \rho \vec{V} = 0$$
$$\rho \frac{\partial \vec{V}}{\partial t} + \rho(\vec{V}.\nabla)\vec{V} = \nabla p + \rho \vec{g} + \nabla . \tau_{i.j} \quad (5)$$

where ρ, $\vec{V}$, t, p, and τ corresponds to density, velocity, time, pressure and shear stress respectively.

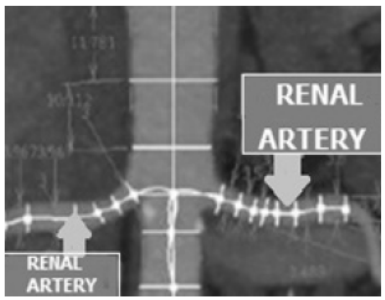


Complexities: artery simulation

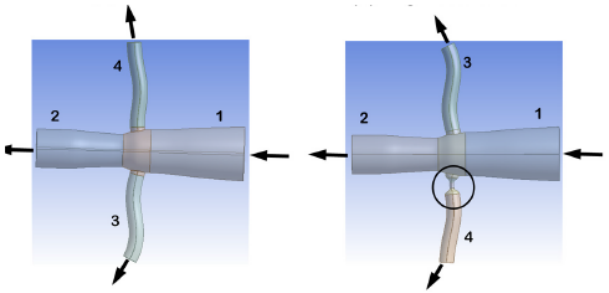
- Difficulty in obtaining geometry -Idealised geometry, computed tomography, MRI and ultrasound imaging.
- Implementation of the proper boundary conditions; *in vivo* measured by MRI, Doppler ultrasound, pressure wire, and other non-invasive techniques; BCs considering the behaviour of arterial network
- Blood viscosity modelling- Newtonian, Casson, K-L, Modi ed Casson, Carreau, Carreau-Yasuda, Cross, Power-law, Modi ed Power-law, Generelized Power-law etc.
- Transient flow during cardiac cycle
- Fluid Structure Interaction-Non linear elastic wall
- Exact Properties-Blood, wall, atheroma etc.

CFD for stenosed artery

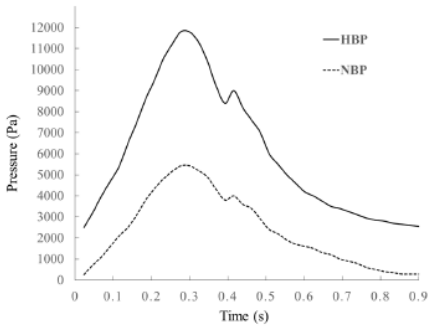
Numerical Study of Stenosed Renal Artery using Fluid – Structure Interaction [1]; Domain and BCs



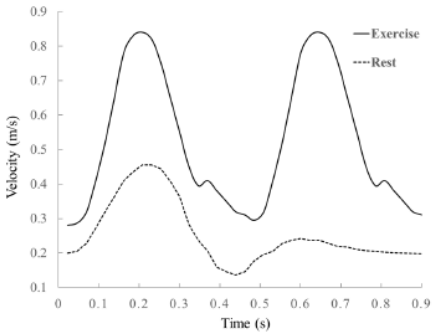
(a) Geometry from the CT slice



(b) CFD model generated



(c) Pulsating pressure at the outlet

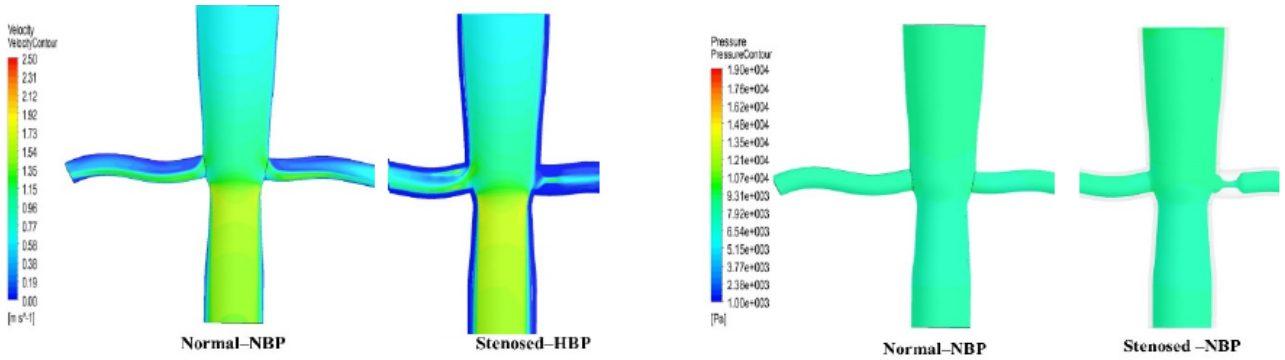


(d) pulsating velocity at the inlet

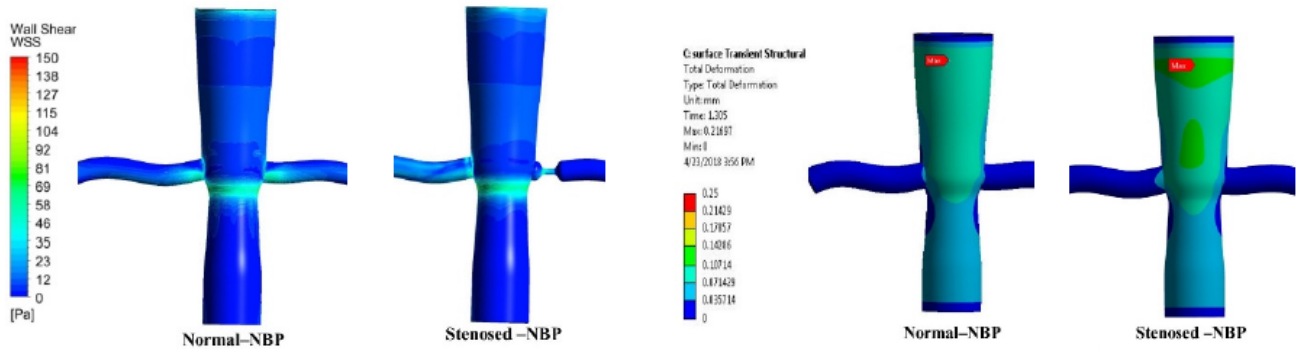
[1] Basri,et al. "Numerical Study of Haemodynamics Behaviour in Normal and Single Stenosed Renal Artery using Fluid–Structure Interaction." Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 51.1 (2018): 91-98.

Results

Results from idealistic abdominal aorta with renal branches with the normal and single stenosed cases under NBP [1]



Comparison of Velocity and pressure contour during NBP

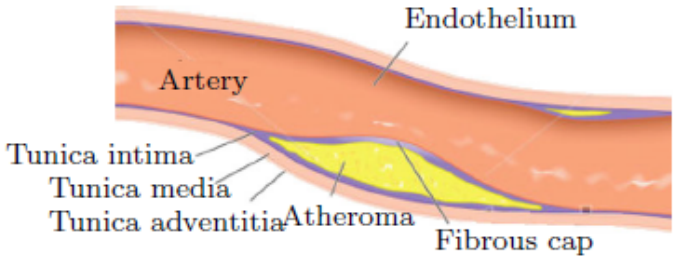


Comparison of WSS and wall deformation during NBP

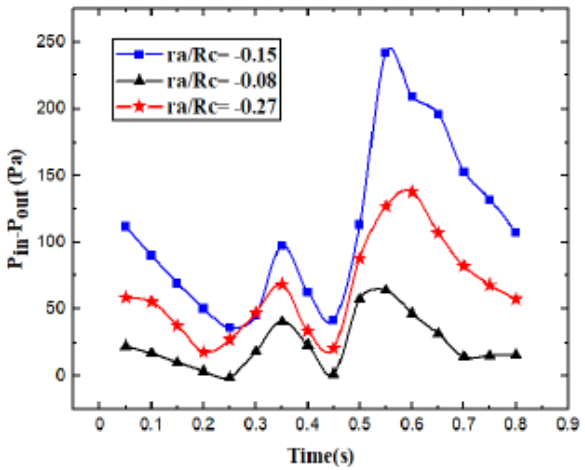
[1] Basri,et al. "Numerical Study of Haemodynamics Behaviour in Normal and Single Stenosed Renal Artery using Fluid–Structure Interaction." Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 51.1 (2018): 91-98.

Results from our study

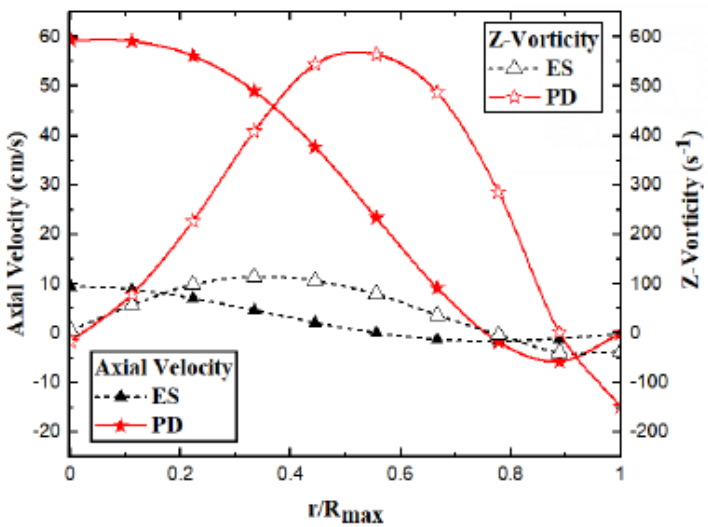
Coronary arterial flow with arterial wall consists of a thin layer tunica intima, atheroma and a thick wall; with varying stenosis severity- FSI Model; Results

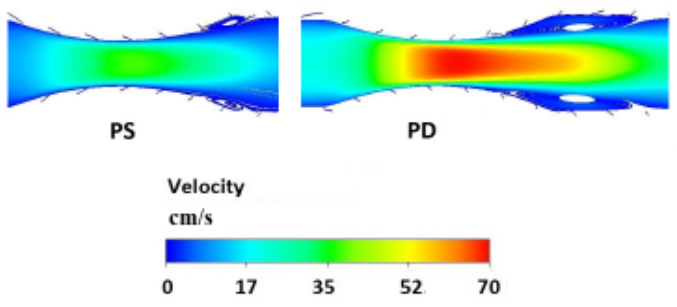


Representation of atheroma



Pressure drop for various stenosis cases





Axial velocity and vorticity at stenosis downstream

Human thermal regulation model

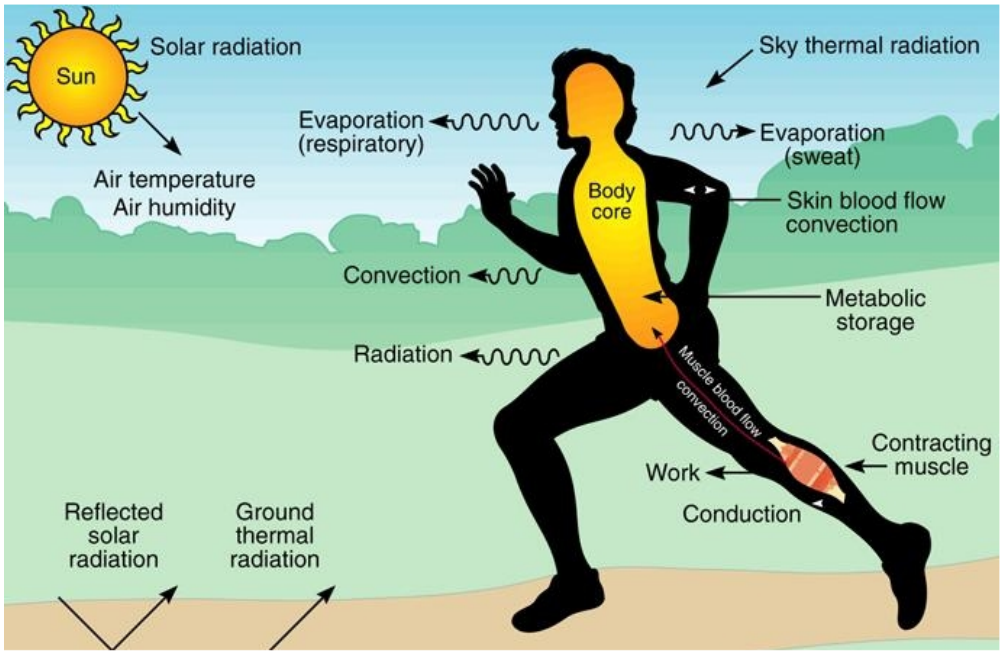
Why?

- Obtaining reasonable estimates of dynamic thermophysiological responses to a variety of environmental conditions.
- Experiments with humans can be life threatening.
- Predict the time dependant temperature distribution & overall comfort level

USE

- To predict the comfort needs of a astronaut wearing a LCG and performing EVA
- To serve as a primary human thermal analysis tool for support of the development of the Space Suit System (SSS)
- Will offer operational simulations and objective evaluation under extreme environments
- To evaluate off-design scenarios without the expense or risk to life

HT Mechanisms



Heat in + Production (Thermogenesis)

- Conduction/Radiation from warm air
- Metabolic activity

Heat Loss (Thermolysis)

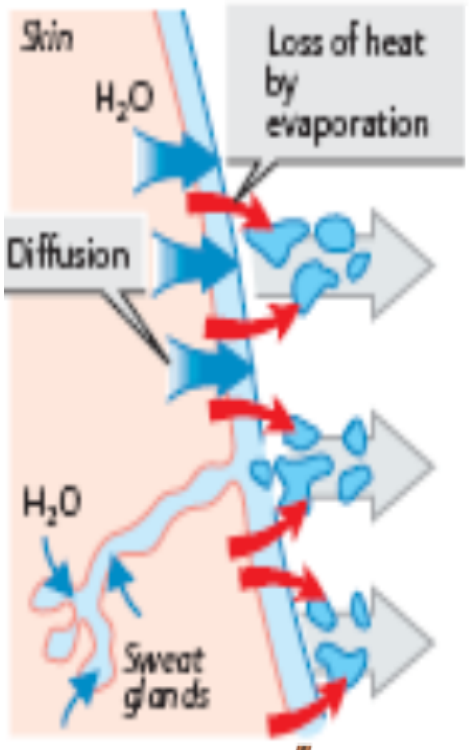
- Conduction (depends on $\partial T/\partial x$)
- Convection (+ conduction 35%)
- Radiation (10%)
- Evaporation (55%, effective at high T_{amb})
- Perspiration
- Respiration
- Loss through urine & feces

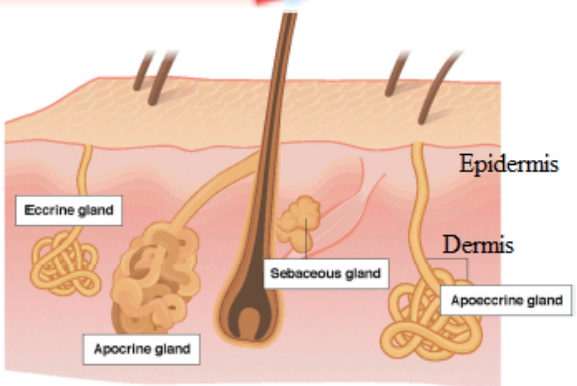
Humans can also affect their body temperature by changing their behaviour e.g. wearing different clothes, seeking shade

Evaporation control

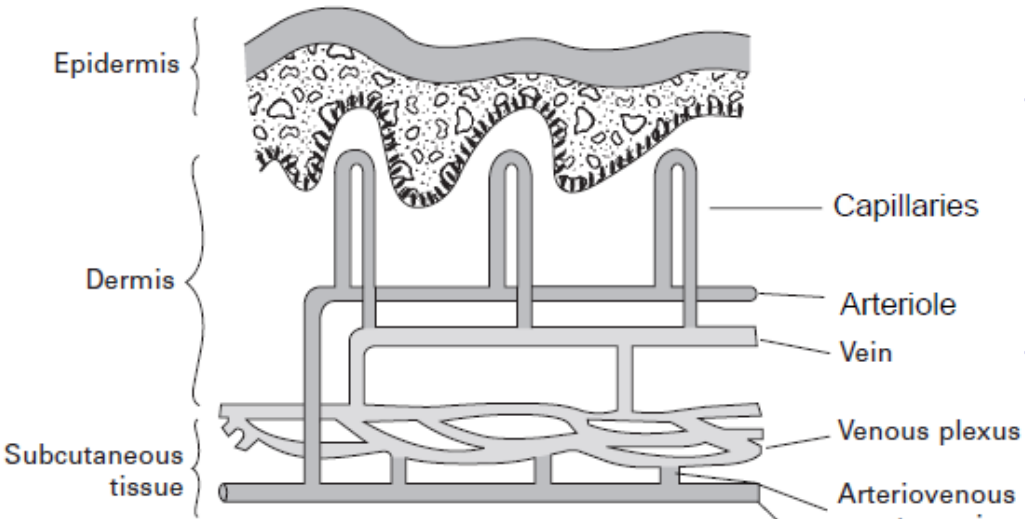
Evaporation of sweat, 100 - 150 mL/day m^2 & Respiratory tract vaporn.(8% Heat Loss)

- Types of sweat glands
  - Eccrine,distributed across nearly the entire body $2-4 million$ in total, Found more in palms, soles, & Face, trunk, and limbs are 2-5 fold lower
  - Apocrine, located primarily in the armpits, pubic region,etc
  - Apoeccrine, contained to only the axillary region



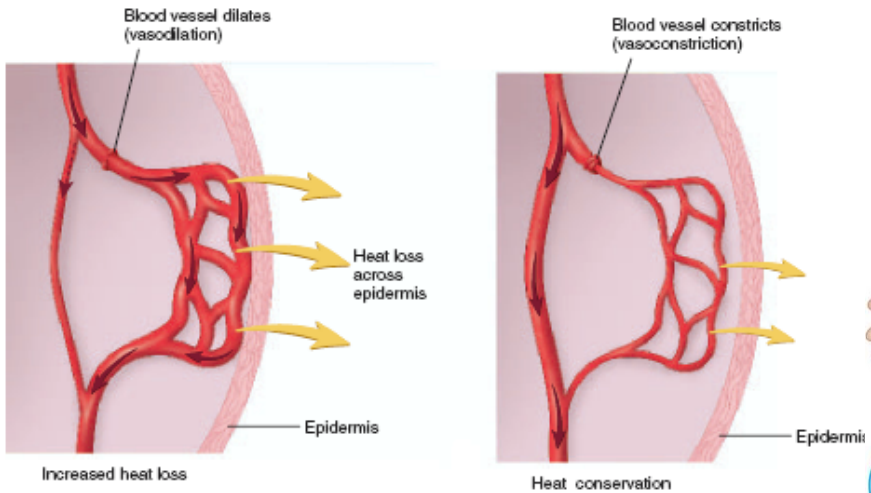


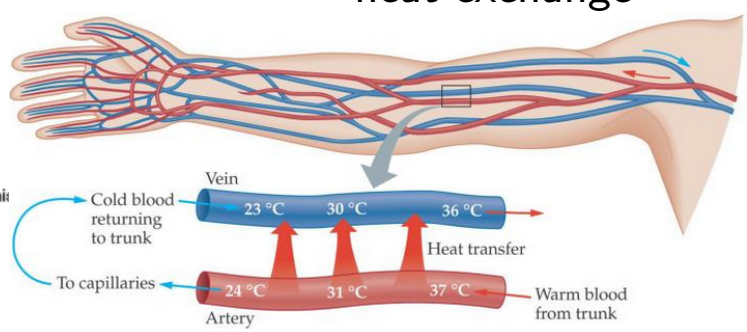
Convection and Radiation control



Vascular system in the skin From Guyton and Hall, 2000: *Textbook of Medical Physiology*

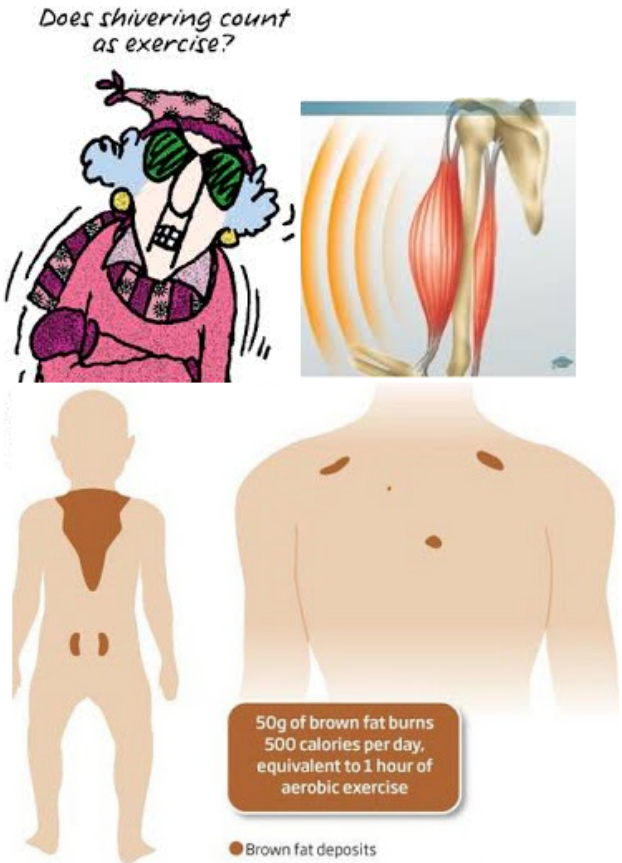
- Cold environment
  - Vasoconstriction
  - Blood circulation $\Downarrow$
  - $\partial T/\partial x \approx 10K$
- Hot environment
  - Vasodilatation
  - Blood circulation $\Uparrow$
  - $\partial T/\partial x \approx 1K$
  - AVA opens
- Another vascular feature
  - Counter-current heat exchange





Heat production

- Adults
  - Shivering, metabolic heat production associated with muscle activity
- Infants until 3-6 months of age
  - Nonshivering thermogenesis, metabolism in brown fat, generates three hundred times more heat



Systems

Passive system

- Depends on
  - Human body and the HT phenomena occurring in it and at its surface
  - Geometric and anatomic characteristics of the human body
  - Thermophysical and the basal physiological properties

Active system

- Regulated by nervous feedback mechanisms
- Controlled by the hypothalamus
- Regulation through regulatory responses
  - Autonomic
  - Somatic
  - Endocrine
  - Behavioural changes
- Major parameters $T_{hyp}, T_{skin}, \& \partial T_{skin}/\partial t,$

Systems Interaction

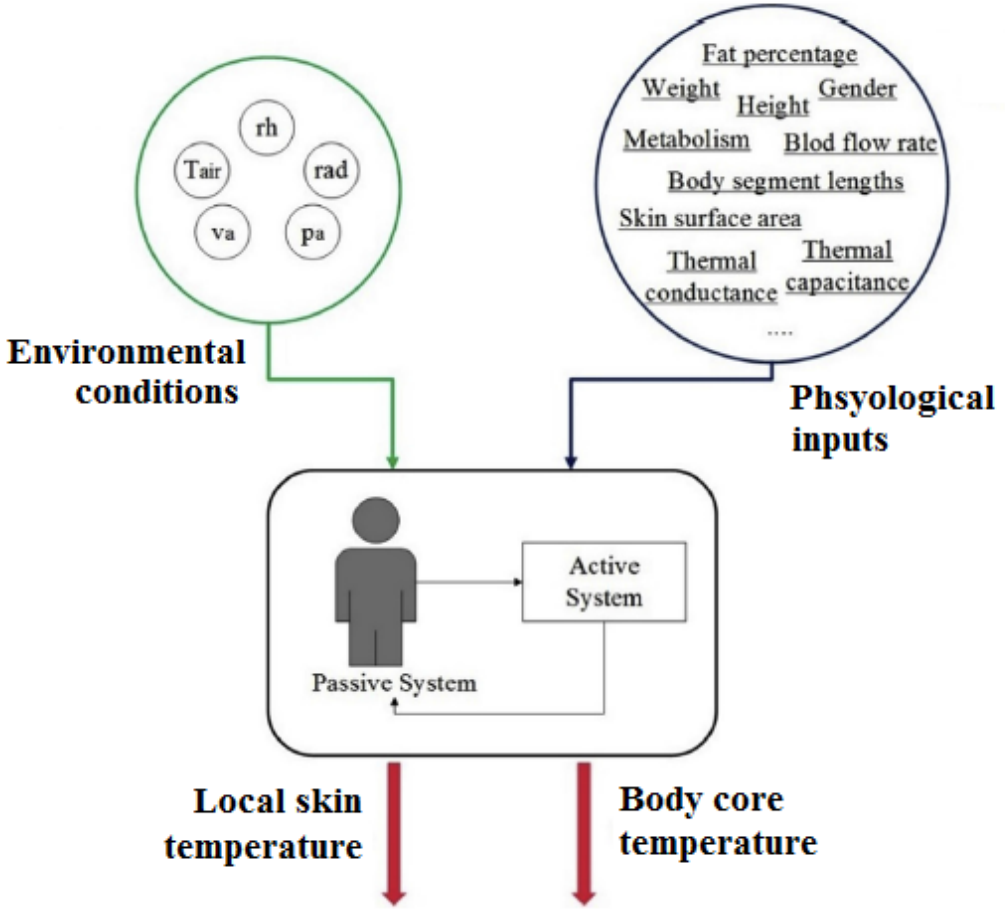


Figure: Schematic view of the inputs and outputs for thermophysiological model.

Passive system

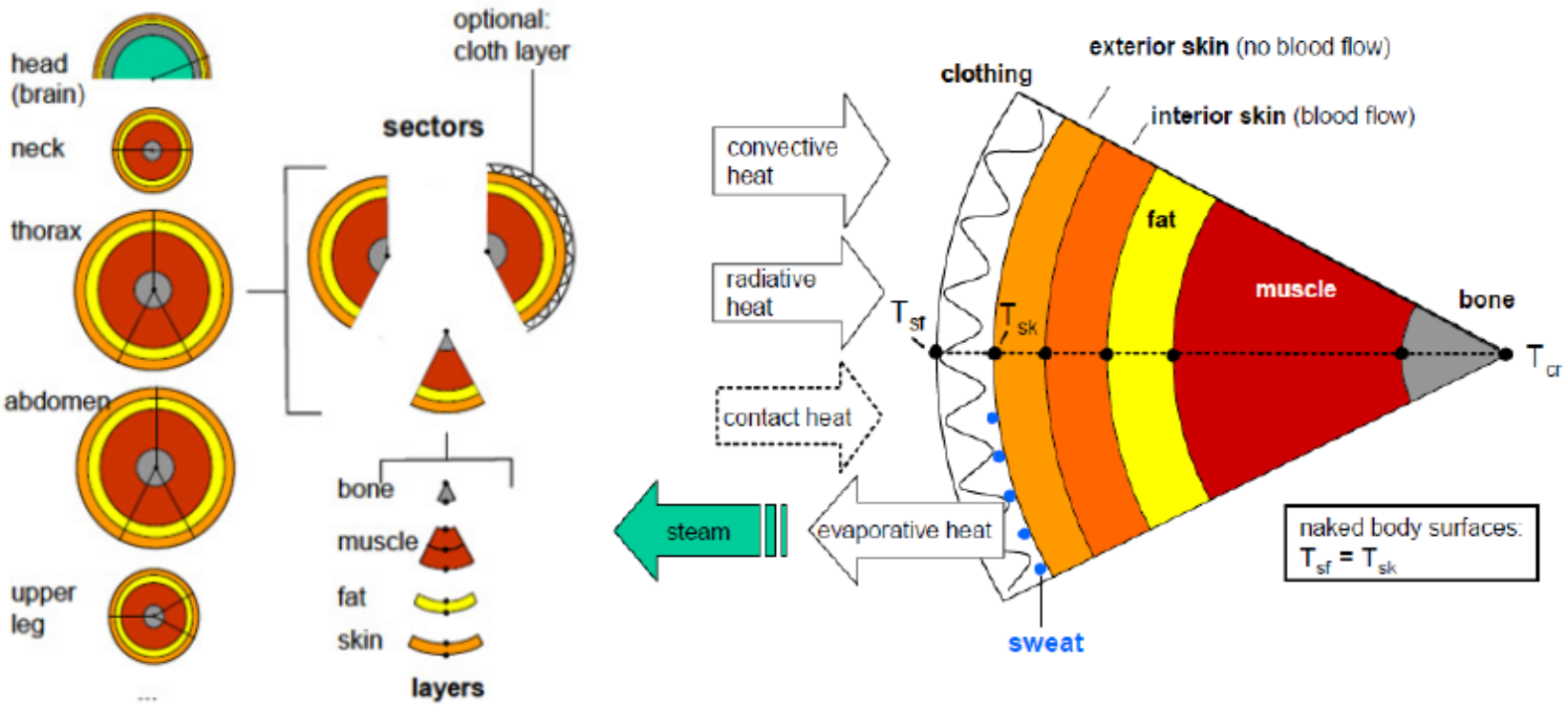


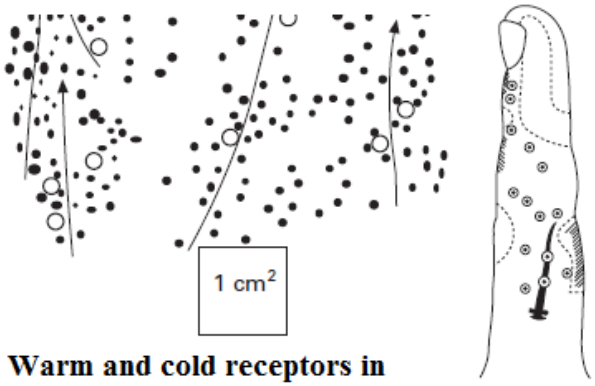
Figure: Heat transfer within segment layers and between the segment and the environment, *[P+Z Engineering GmbH, THESEUS-FE Theory Manual Version 5.0.09, 2016]*

Bioheat equation is used to model the heat transport.

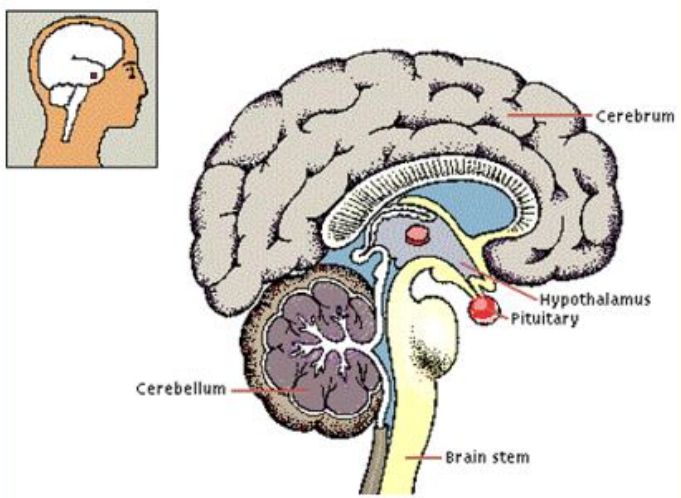
$$\nabla . k \nabla T + q_m - w c_p (T - T_a) = \rho c_p \partial T / \partial t$$

Active system

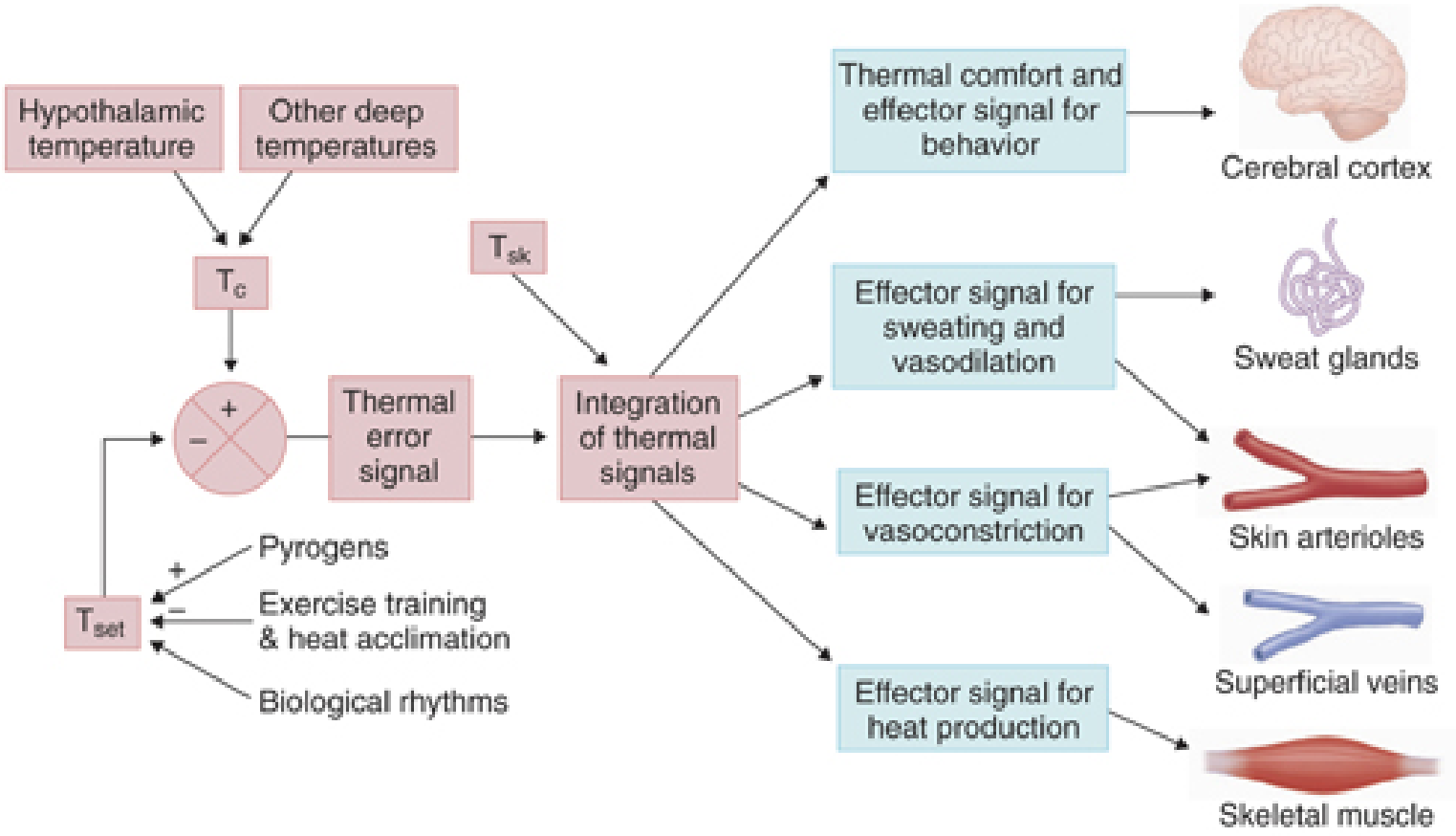
- Thermoafferent system:
  Sensors, 4types, more sensitive to cold, skin in face, neck and chest contain 5-times more
- Integrating system:
  at several levels of the CNS, hypothalamus is the center for thermoregulation, Acts as a thermostat, Evaluates input and Sends output
- Effector system:
  autonomic nerve system is involved - Receives output, Produces a response- vasodilatation,sweating, vasoconstriction, shivering



Warm and cold receptors in the dorsal forearm



Active system



Thermophysiological models

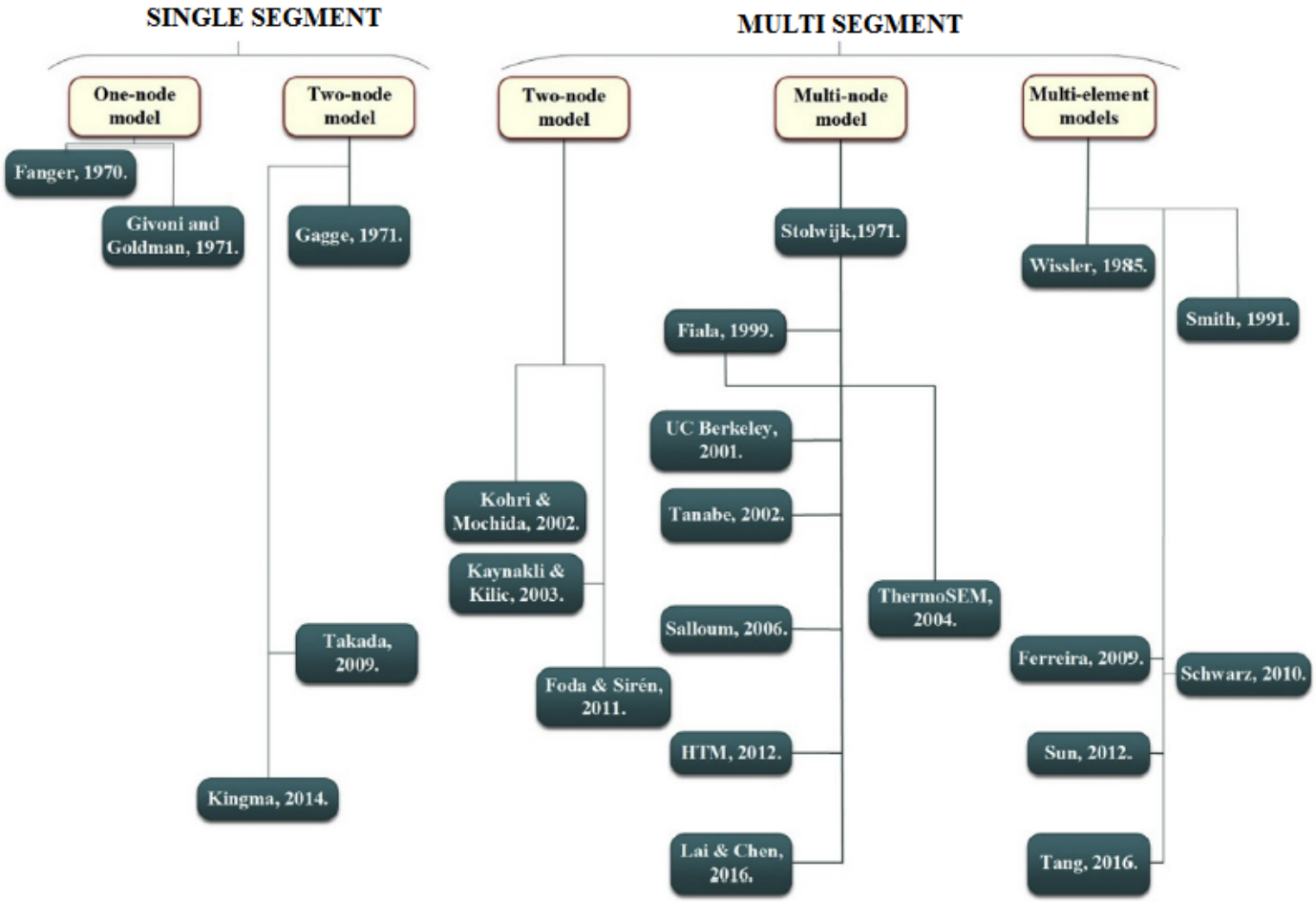


Figure: Thermophysiological models through the years., *[Katic, K., Li, R., & Zeiler, W. (2016). Thermophysiological models and their applications: A review. Building and Environment, 106, 286-300.]*

NASA Models

Models used by NASA

- A 25-node Stolwijk model for design of PLSS for Apollo missions [1].
- 41-node model for LCG) for space suit design including the EMU [2].
- Wissler model 15 segment, 225-node whole-human model [3].
- Modification of Wissler model incorporating to incorporate LCVG- and adopted for analysis and design guidance to the Constellation Program [4].

[1] J. A. Stolwijk, A mathematical model of physiological temperature regulation in man, Tech.rep., NASA CR-1855, 1971.
[2] L. H. Kuznetz, Control of thermal balance by a liquid circulating garment based on a mathematical representation of the human thermoregulatory system. PhD thesis, California Univ., Berkeley, 1976.
[3] E. Wissler et al., Mathematical simulation of human thermal behavior using whole body models, Heat transfer in medicine and biology, vol. 1, no. 13, pp. 325-373, 1985.
[4] K. L. Nyberg, K. R. Diller, and E. H. Wissler, Model of human liquid cooling garment interaction for space suit automatic thermal control, J. Biomech. Eng., vol. 123, no. 1, pp. 114 120, 2001.

Stolwijk's Model

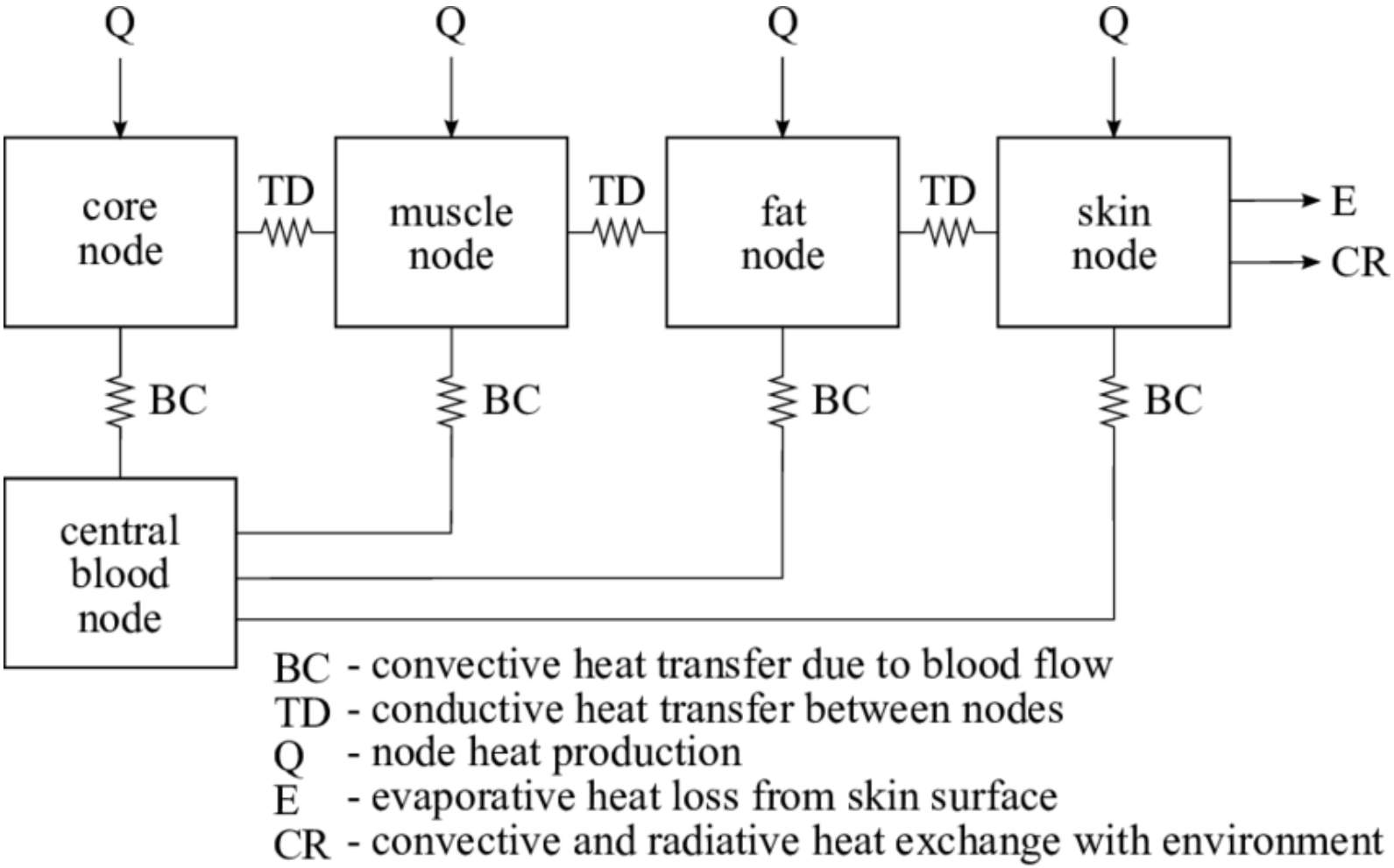


Figure: Passive system of the body segment in the Stolwijk's model (*J. Stolwijk, A Mathematical Model of Physiological Temperature Regulation (NASA Contractor Report, 1971.*)

Stolwijk's Model

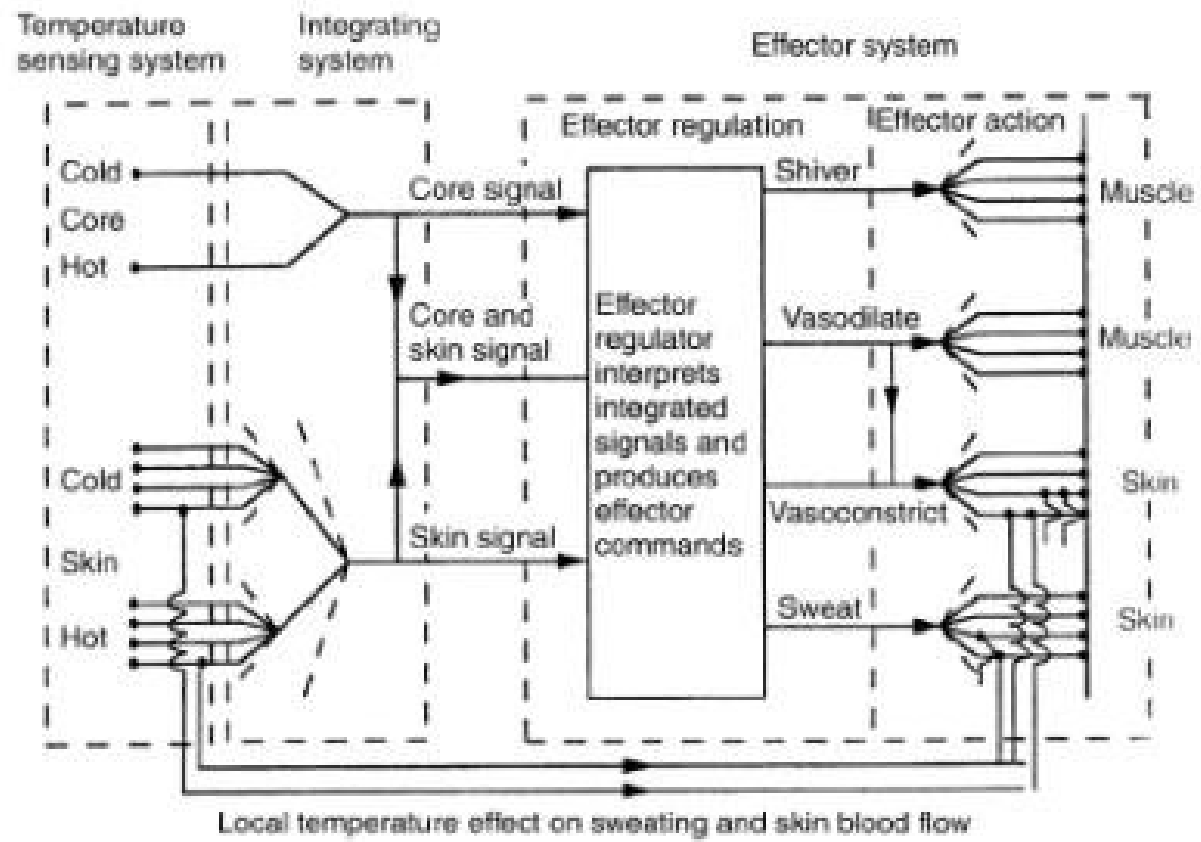
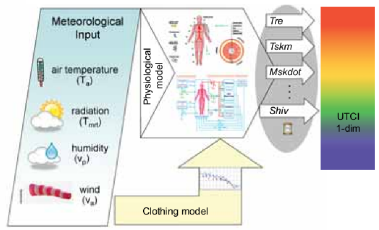
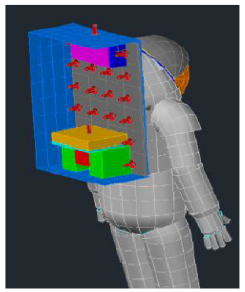


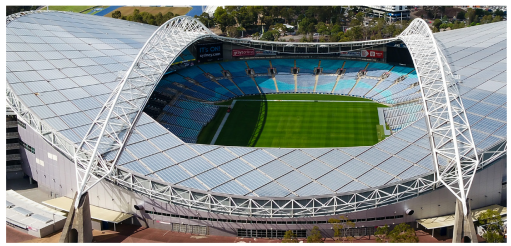
Figure: Active system of the body segment in the Stolwijk's model (*J. Stolwijk, A Mathematical Model of Physiological Temperature Regulation (NASA Contractor Report, 1971.*)

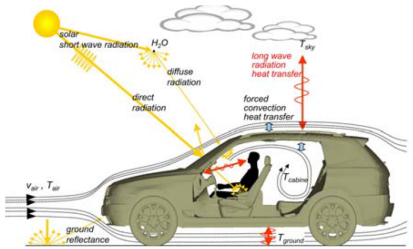
Applications

- The Universal Thermal Climate Index (UTCI):
  Current model used has 187 nodes, 12 compartments.
  Started in 2005, 19 countries.
- Predicting the temperature of the patients during heart surgery:
  Assessing the effect of changing conditions on the body temperature distribution
- For the clothing research:
  Design of space suit, Crew Escape Suit, fire fighting wears, sleeping bags, mattresses etc.
- Design of sports stadiums, buildings:
- Assessing the thermal comfort in a car cabin:









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