Multimodal Sensing for Thermal Comfort and Energy Saving in Smart Buildings

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Junxian Yang and Huihe Qiu

Department of Mechanical and Aerospace Engineering
Hong Kong University of Science and Technology
Hong Kong

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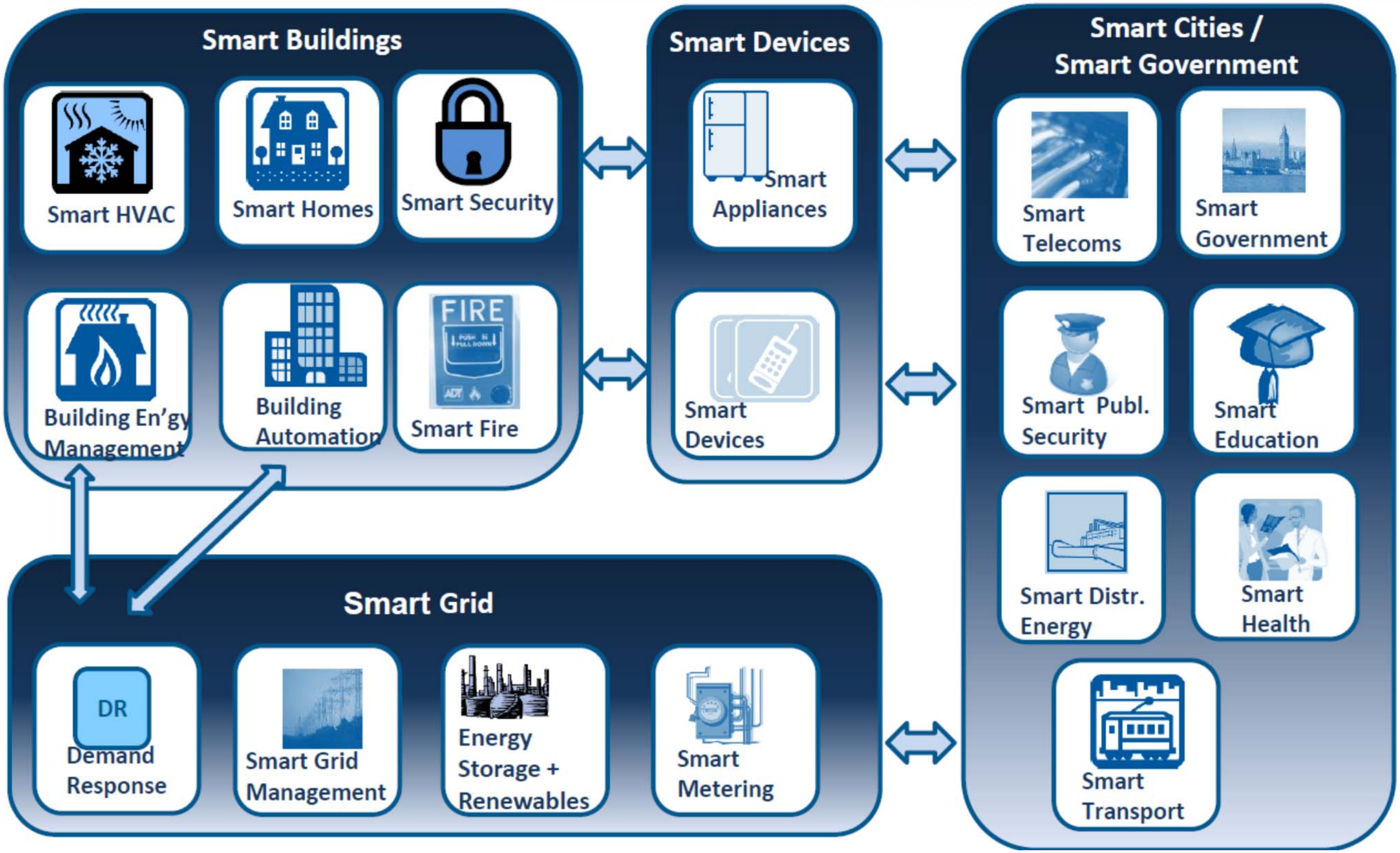
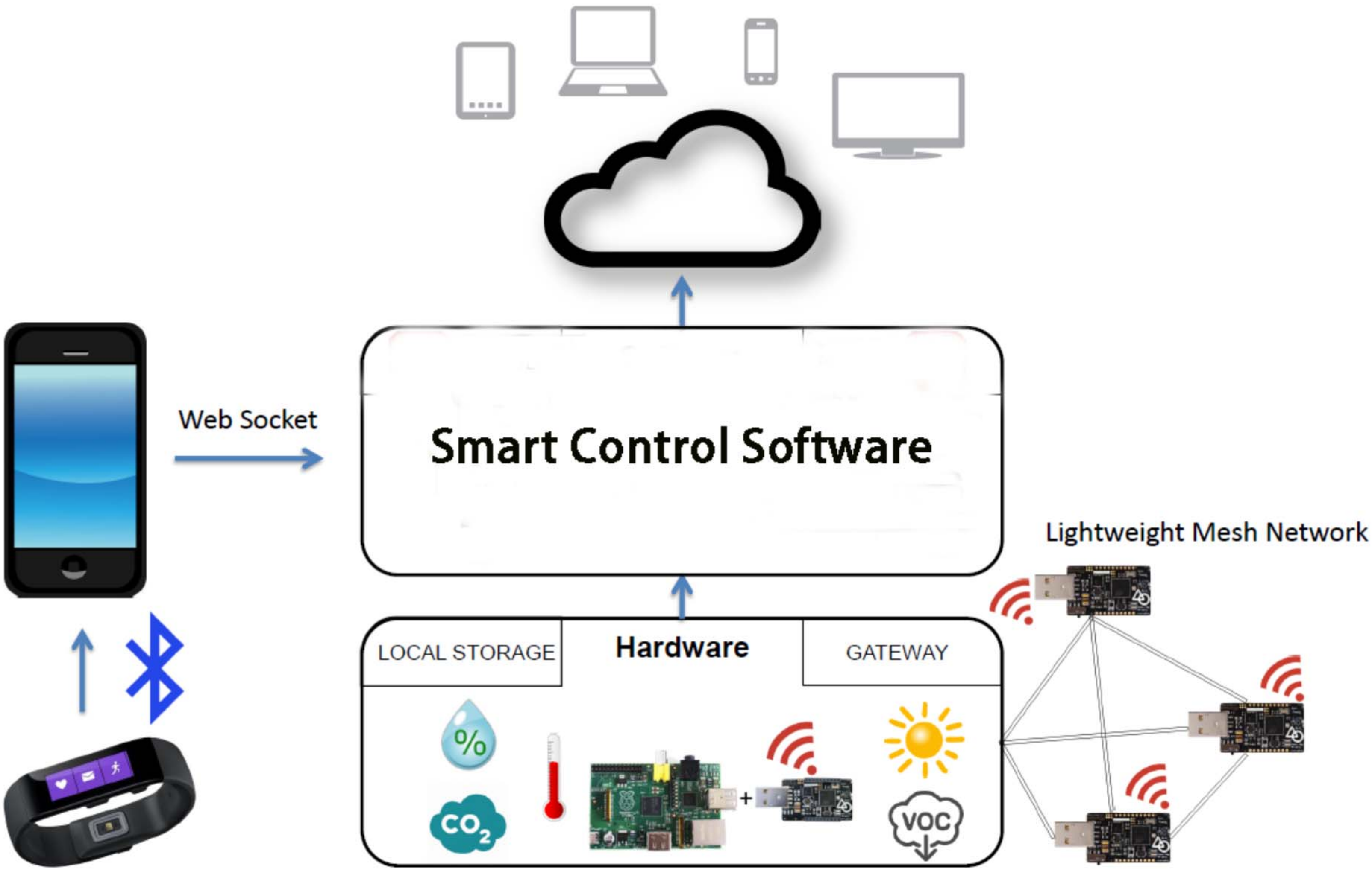
Smart Evolution---Smart World

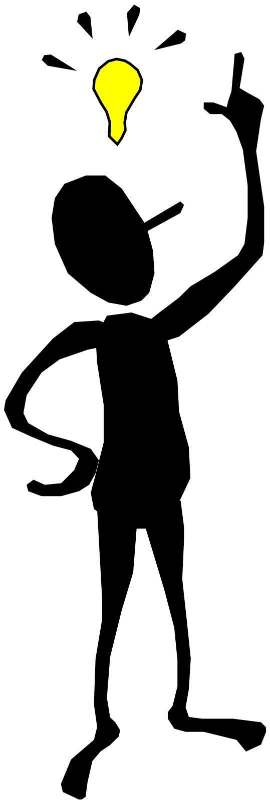


Courtesy BSRIA 2015

IoT Based Thermal Comfort in Smart Buildings



How to Define Thermal Comfort



www.dantecdynamics.com

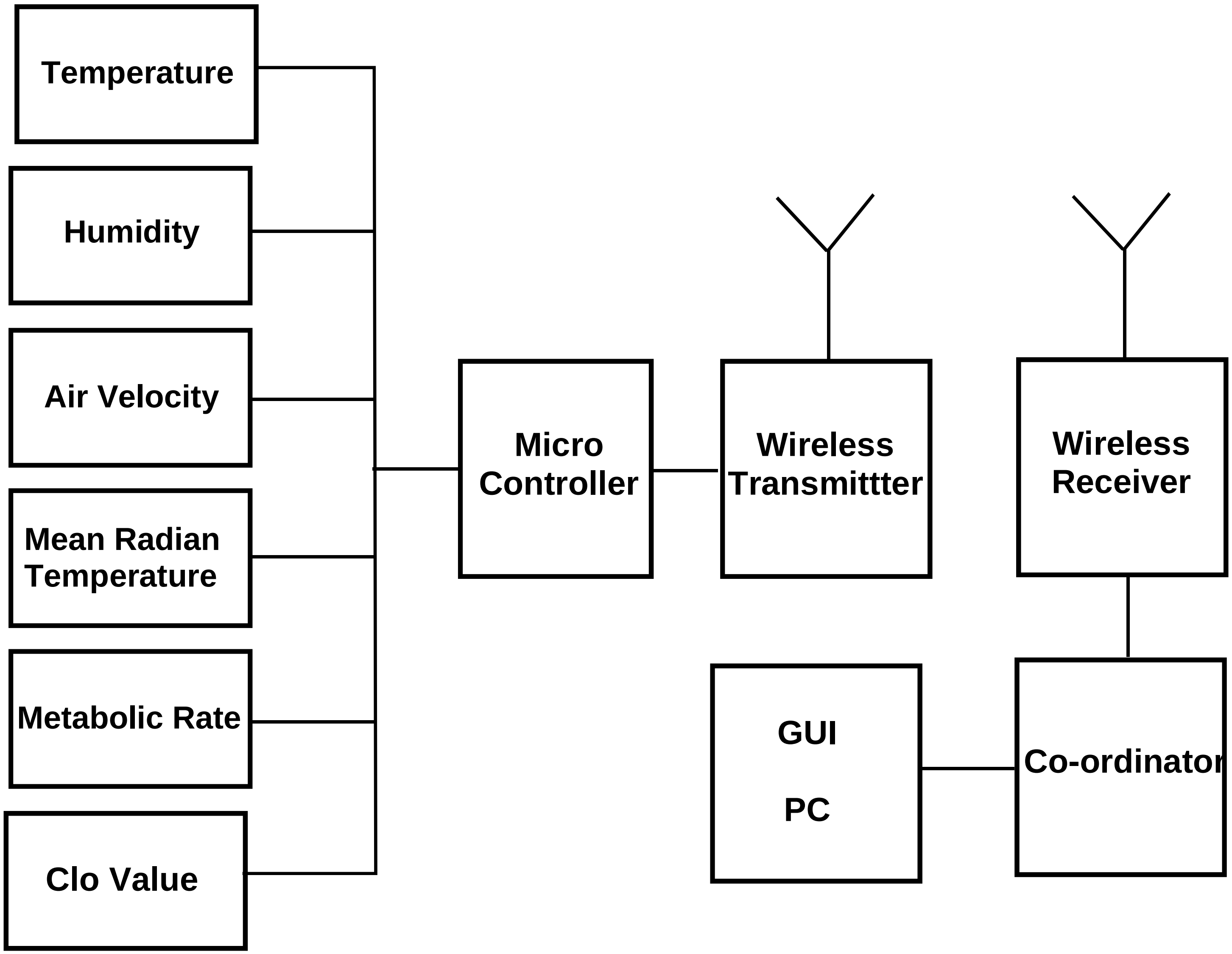
Fanger's Equation

$$PMV = \left(0.028 + 0.3033e^{-0.036M}\right) \times \left\{(M - W) - 3.05 \times 10^{-3}\left[5733 - 6.99(M - W) - P_a\right] - 0.42\left[(M - W) - 58.15\right] - 1.73 \times 10^{-5} M\left(5867 - P_a\right) - 0.0014M\left(34 - T_a\right) - 3.96 \times 10^{-8} \times f_{cl}\left[\left(T_{cl} + 273\right)^4 - \left(T_{mrt} + 273\right)^4\right] - f_{cl} \times h_c\left(T_{cl} - T_a\right)\right\}$$

$$T_{cl} = 35.7 - 0.028(M - W) - 0.155I_{cl}\left\{3.96 \times 10^{-8} f_{cl}\left[\left(T_{cl} + 273\right)^4 - \left(T_{mrt} + 273\right)^4\right] + f_{cl}h_c\left(T_{cl} - T_a\right)\right\}$$

$$h_c = \begin{cases} 2.38\left(T_{cl} - T_a\right)^{0.25} & \text{for } 2.38\left(T_{cl} - T_a\right)^{0.25} \geq 12.1\sqrt{\mathrm{V_{air}}} \\ 12.1\sqrt{V_{air}} & \text{for } 2.38\left(T_{cl} - T_a\right)^{0.25} \leq 12.1\sqrt{\mathrm{V_{air}}} \end{cases}$$

Wireless Sensor Networks for PMV Control

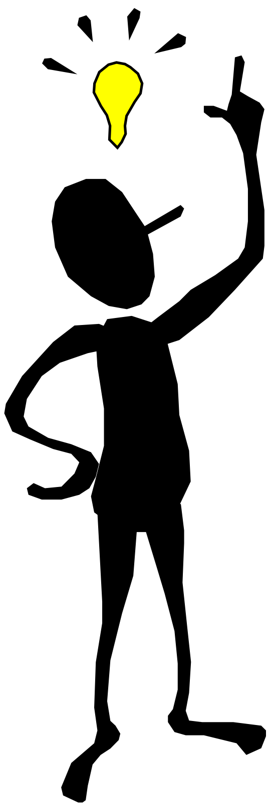


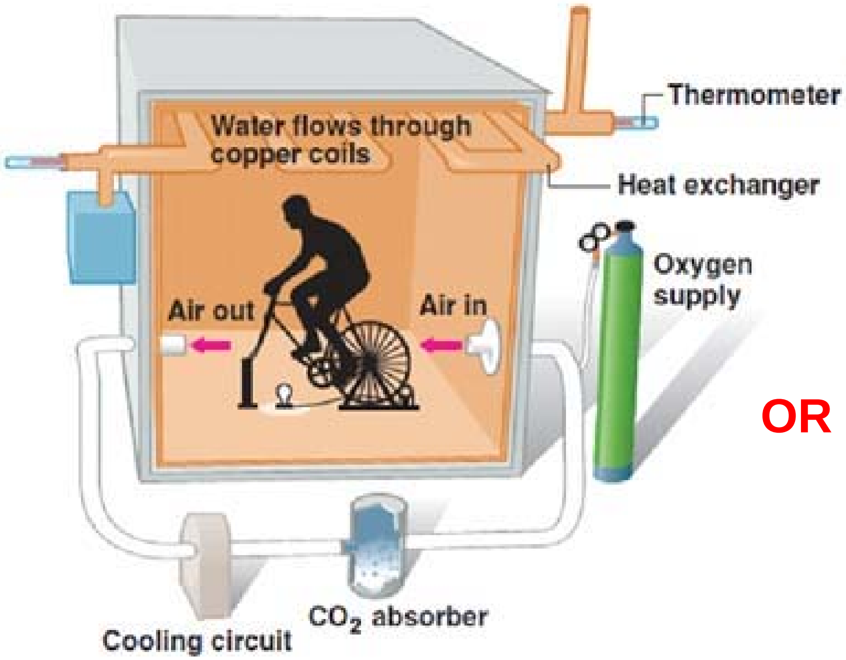
Challenges

According to a sensitivity analysis, the most influencing variables are:

- **Clothing values**
- **Metabolic rates**

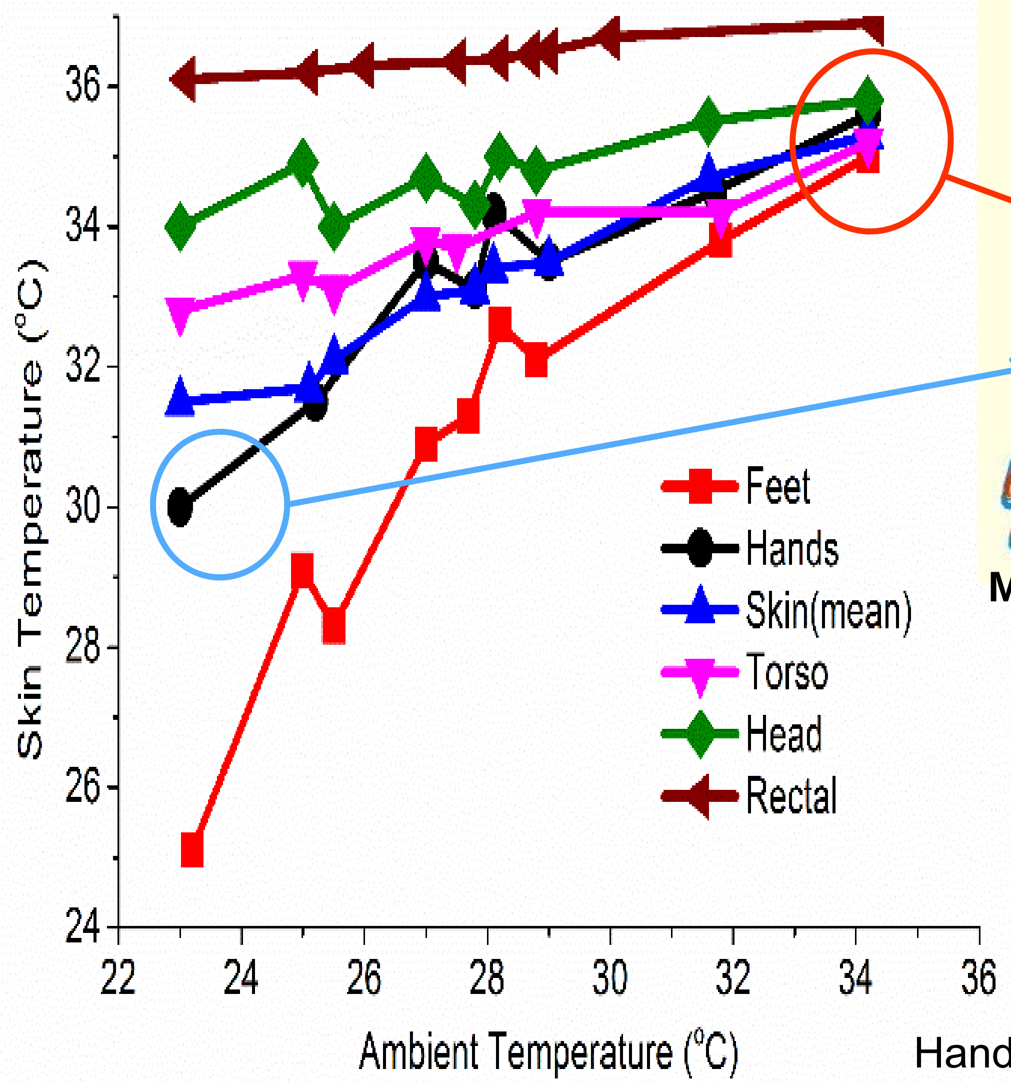
How to Measure Metabolic Rate for Thermal Comfort Control?

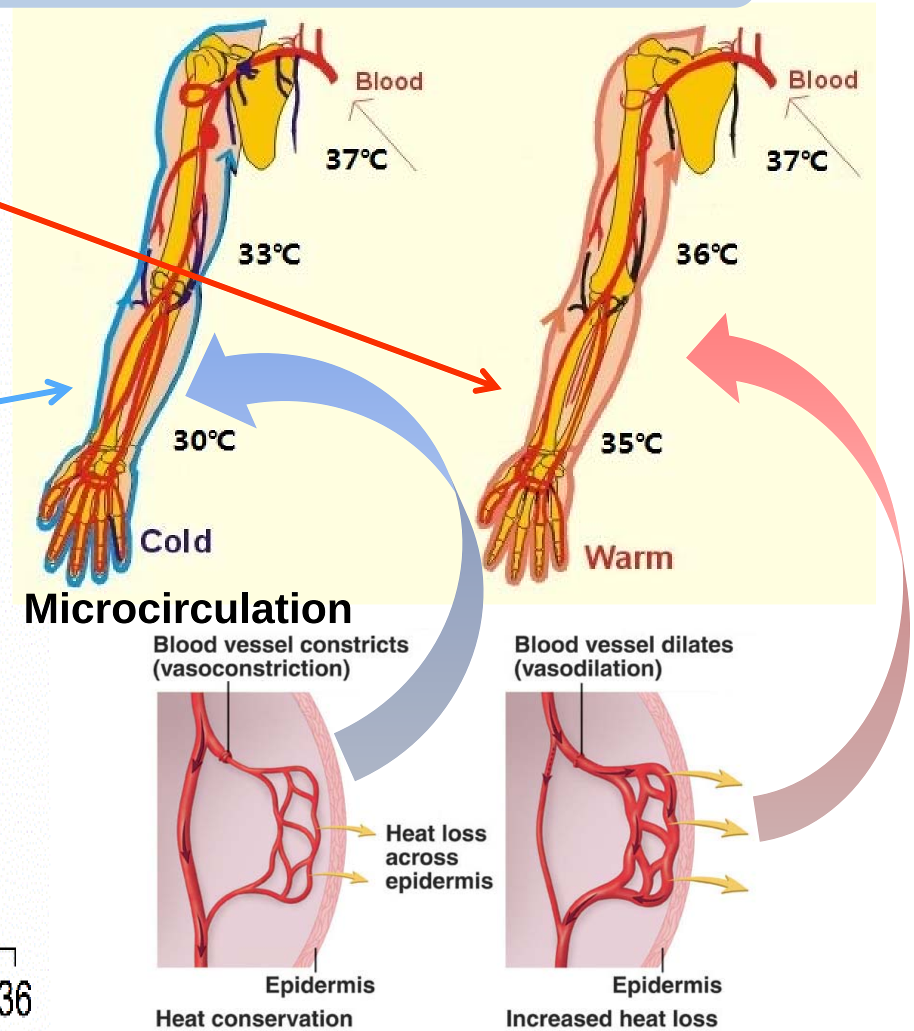




OR

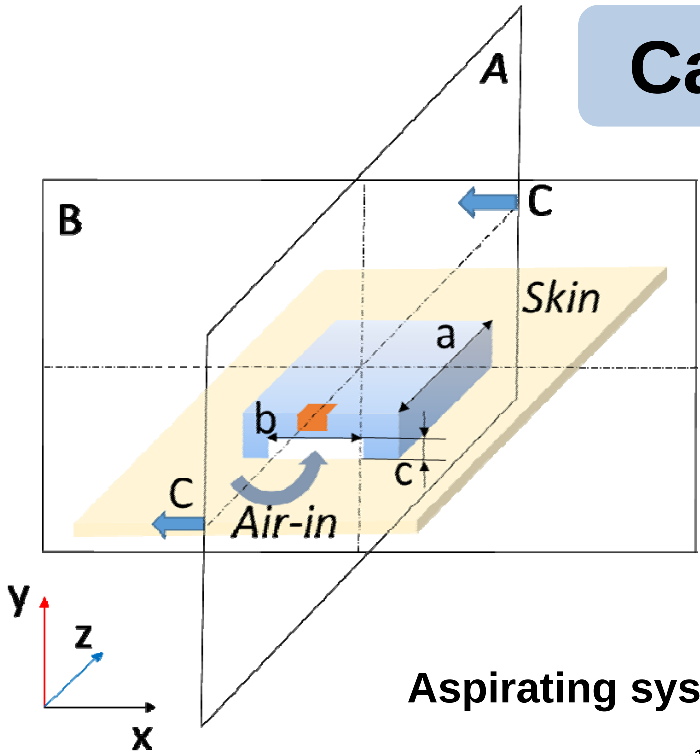
Thermal Balance and Thermoregulation

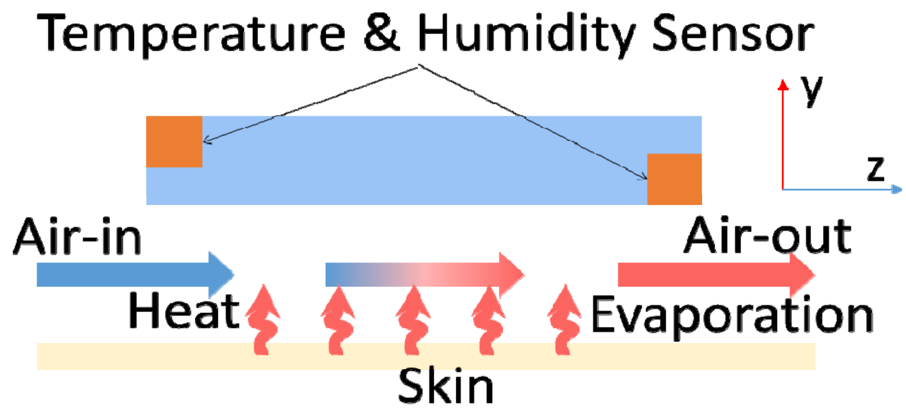




Hands have a big temperature difference between cold and hot environment. This feature apparently indicates the heat loss and microcirculation of hands can be utilized to estimate the metabolic rate and evaluate the thermal sensation.

Calibration of Microenvironment





Aspirating system for heat loss measurement

Relative humidity: $\mathrm{RH} = \frac{p_v}{p_s}$, p_s **is the saturated vapor pressure at T.**

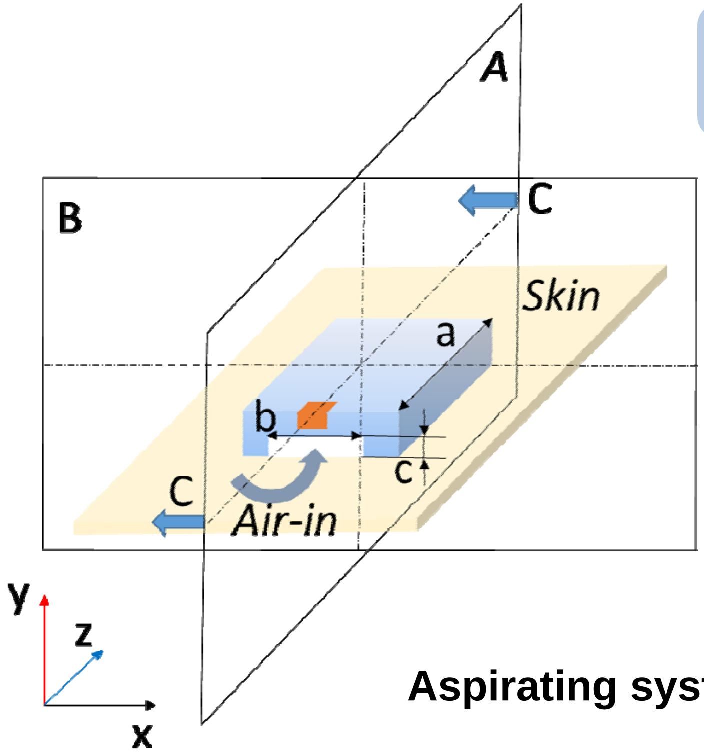
$$\ln p_s = \ln 611.2 + \frac{17.62 * T}{243.12 + T}$$

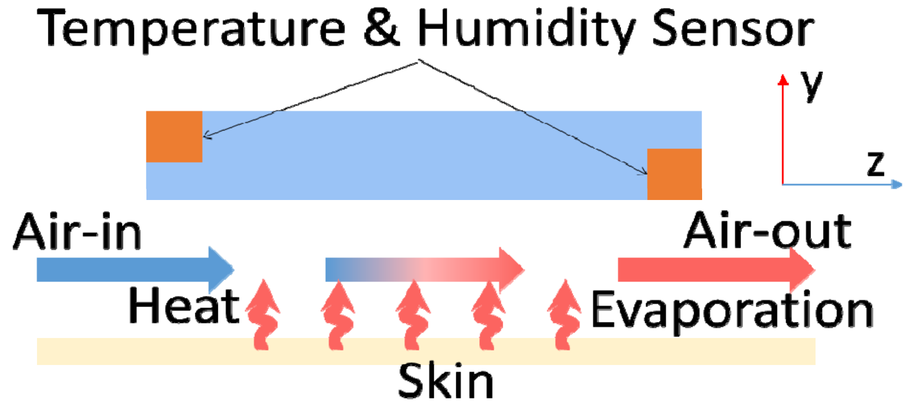
Air volume is V, vapor mass is m_v, **dry air mass is** m_a, **then**

$$\rho_v = \frac{m_v}{V} = \frac{p_v}{R_v T},\ m_v = \frac{p_v * V}{R_v * T},\ m_a = \frac{p_a V}{R_a T} = \frac{(B - p_v)V}{R_a T}$$

p_a **is dry air pressure,** p_v **is vapor pressure,** B **is standard atmospheric pressure.**
R_a **is gas constant of dry air,** R_v is **gas constant of vapor.**

Heat Loss Measurement





Aspirating system for heat loss measurement

The enthalpy of air is defined as the sum of the enthalpy of 1g dry air and that of d g of vapor. For enthalpy calculation, set dry air enthalpy and water enthalpy are 0 at 0℃.

Air enthalpy: $\mathrm{h} = h_a + d * h_v \ (J/\mathrm{g(a)})$

Dry air enthalpy: $h_a = c_a * T \quad (J/\mathrm{g}),\quad c_a \ (J/(g * K)$ **is dry air specific heat at 1 atm;**

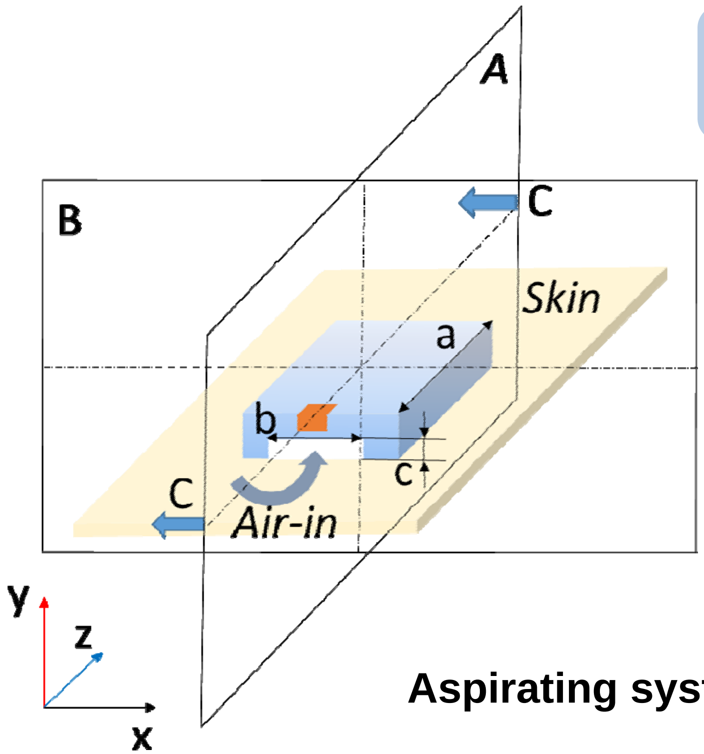
Vapor enthalpy: $h_v = \mathrm{r} + c_v * T \quad (J/\mathrm{g}),\quad c_v \ (J/(g * K)$ **is vapor specific heat at 1 atm;**

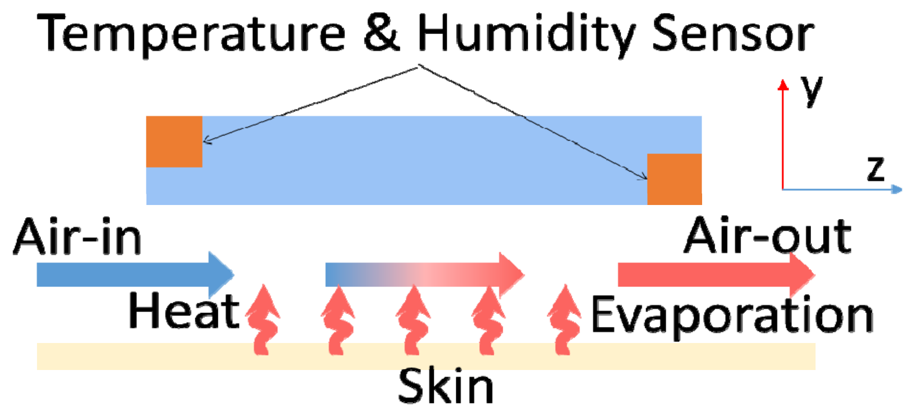
$r \ (J/g)$ **is latent heat of vaporization at 0℃.**

$$\mathrm{h} = h_a + d * h_v = c_a * \mathrm{T} + d * (\mathrm{r} + c_v * \mathrm{T}) \quad (J/\mathrm{g(a)})$$

$d = \frac{m_v}{m_a} \ (g/g\,(a))$, m_v **is the vapor mass,** m_a **is the dry air mass.**

Heat Loss Measurement





Aspirating system for heat loss measurement

Air-in temperature: $T_{in}\ (K)$
Air-out temperature: $T_{out}\ (K)$
Air-in relative humidity: RH_{in}
Air-out relative humidity: RH_{out}
Cover area : $A = ab\ (m^2)$
Skin surface area :

$$A_{Du} = 0.202 \times Weight^{0.425} \times Height^{0.725}$$

Air volume flow rate:$\dot{V}\ (m^3/s)$ **:** $\dot{V}$
Air velocity: $v_{air}\ (m/s)$

$$q = \dot{m}_a * (h_{out} - h_{in})$$

$$\text{HL} = q\frac{A_{Du}}{A}$$

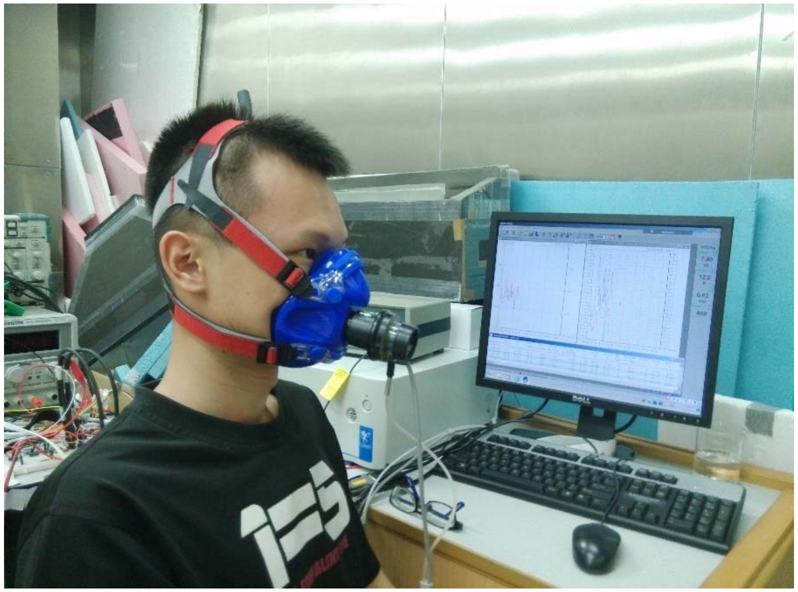
Dry air mass flow rate: $\dot{m}_a\ (g/s)$
Air-in enthalpy: $h_{in}\ (J/g)$
Air-out enthalpy: $h_{out}\ (J/g)$
Heat loss: $\mathrm{HL}(kcal/min)$

Metabolic Measurement: Indirect calorimetry

All energy-releasing reactions in the body ultimately depend on oxygen use.

Compared with direct calorimetry, indirect calorimetry remains simple and less expensive

However, still high cost and inconvenient for individuals' daily use



Metabolic Rate Measurement

The TE depends on the type of metabolism that is indicated by the RQ. In the determination of the metabolic rate, a mean RQ of 0.85 is used and $TE_{0.85}$ is equal to 20.36 kJ/L. The maximum possible error is $\pm 3.5\%$, but generally the error will not exceed 1%.

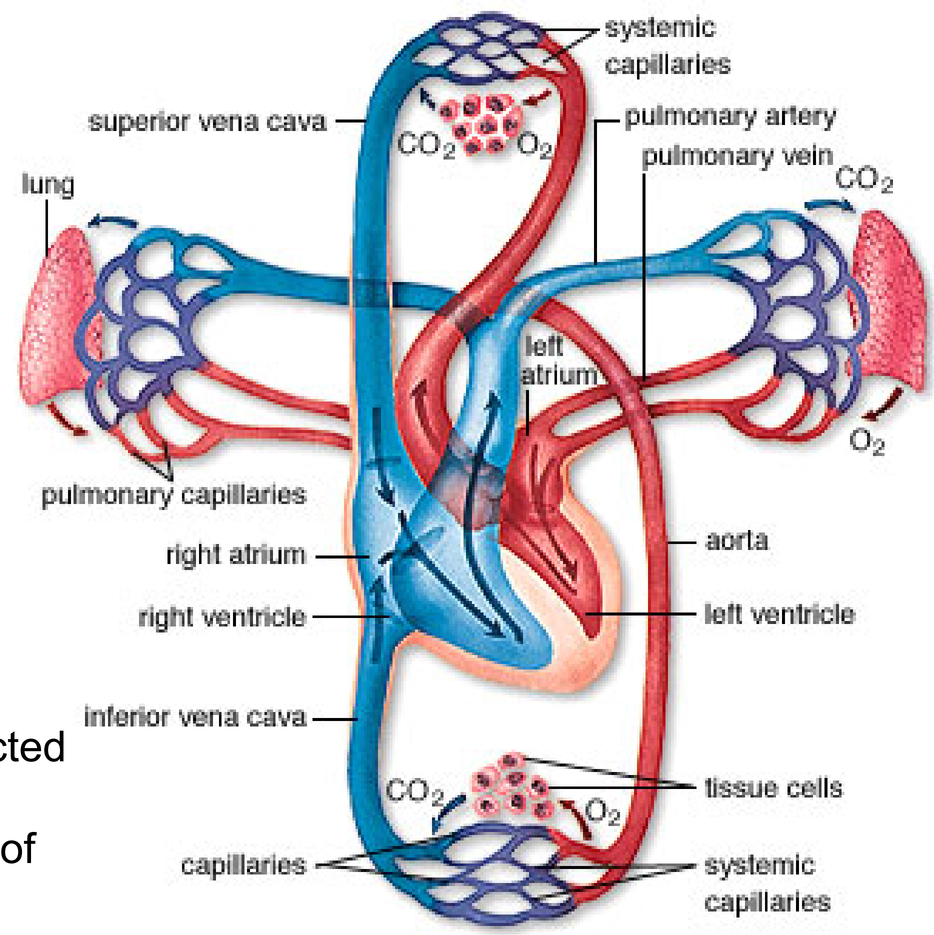
$$MR = TE_{RQ} \times V_{O_2}, \quad TE_{0.85} = 20.36$$

$$V_{O_2} = SV \times HR \times D_{a-\bar{v}O_2}$$

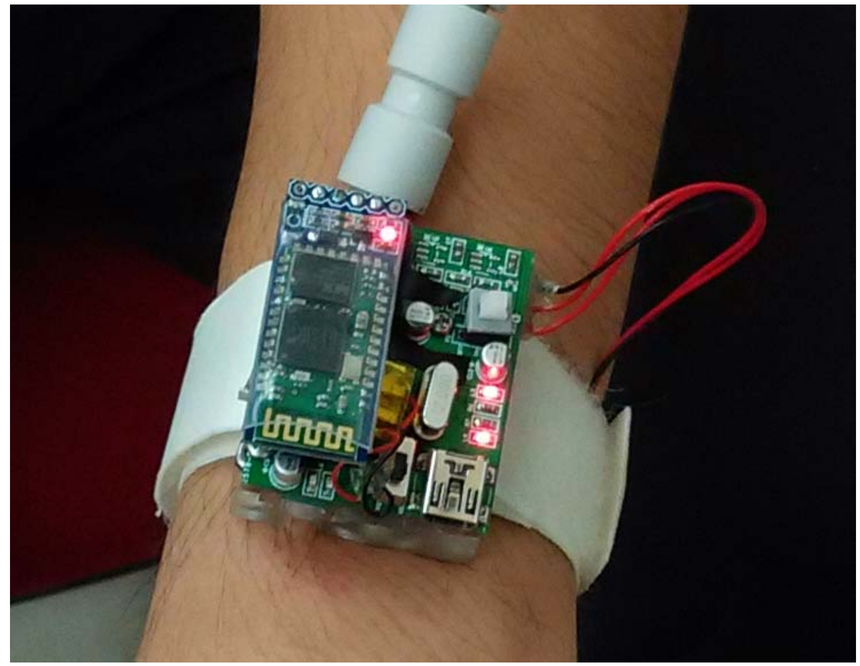
$$MR \propto HR \times SV \times D_{a-\bar{v}O_2} \propto \frac{HR}{|Z|}$$

SV and blood flow rate (oxygen supply) have an impact on skin impedance (microcirculation, vasoconstriction and vasodilation)

V_{O_2}: Oxygen consumption rate (L/s)
HR: Heart rate (bmp)
SV: Stroke volume (L), the amount of blood ejected with each contraction
$D_{a-\bar{v}O_2}$: Difference between the oxygen content of arterial and mixed-venous blood (ml/dl)
$|Z|$: Skin impedance (Ohm)

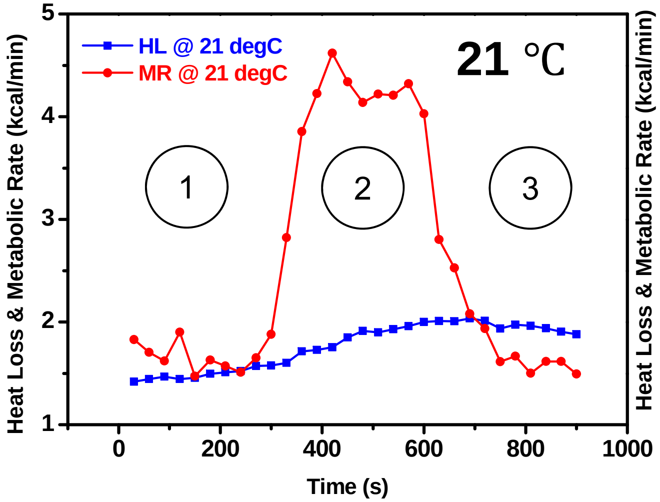


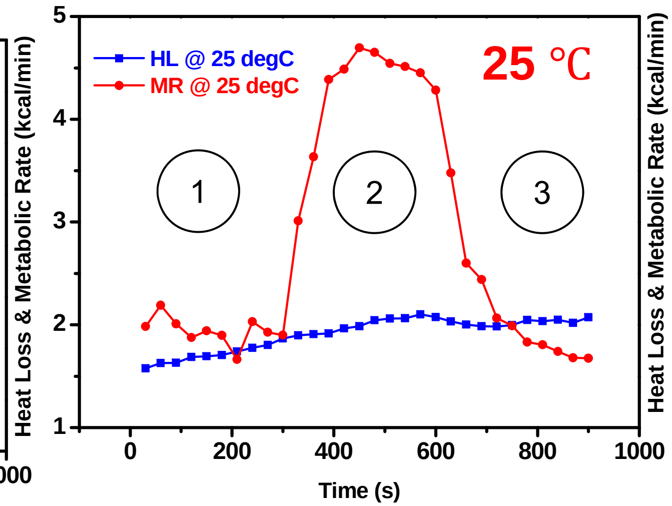
Experimental Setup



Experiments and Results

Temperature: 21, 25, 29 ℃
Relative Humidity: 50%





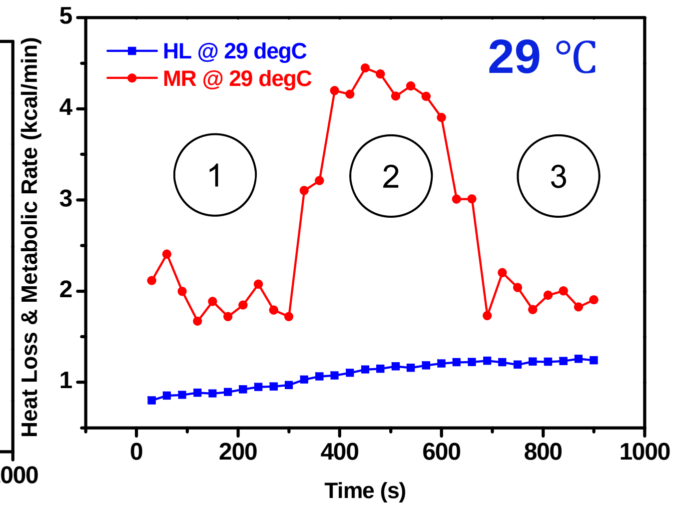
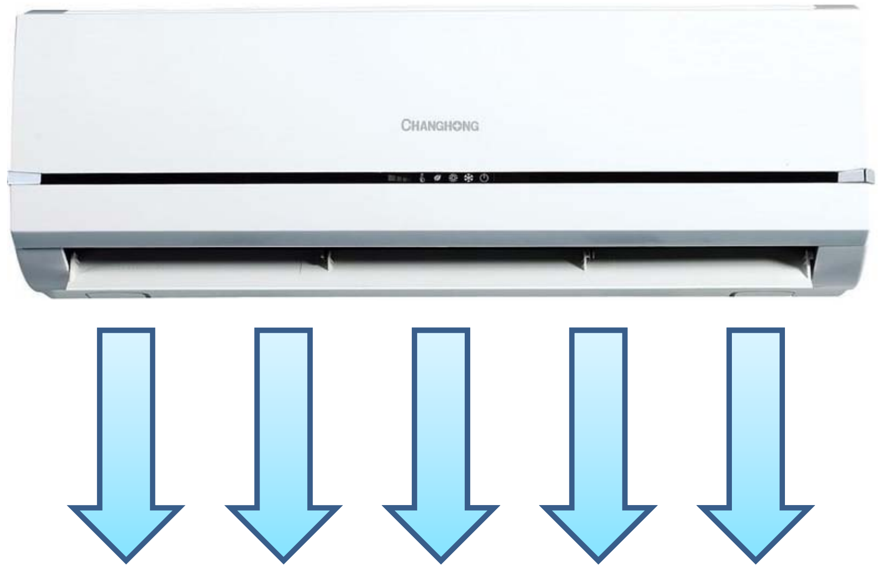


Table 1 Voted and calculated PMV of one subject at the chamber temperature of 21, 25 and 29℃

Temperature (℃)	21			25			29		
Phase	1	2	3	1	2	3	1	2	3
Voted PMV	-1	1	0	0	1	0	1	3	2
Calculated PMV	-1.8	1.0	-1.5	0	2.0	0	1.2	2.6	1.2
Comfort Temperature (℃)	26.2	15.7	25.8	25.1	14.7	25.3	25.4	16.1	24.9

Apply to Thermal Comfort Control and Energy Saving



26℃

Conclusion

- Utilizing human's thermal sensation for thermal comfort control and energy saving in Smart Buildings has been developed.
- A novel approach using heart rate and skin impedance ratio has been developed for predicting human's metabolic rate for thermal comfort evaluation in free-living conditions
- It is possible to predict thermal comfort for PMV based control and energy saving in buildings
- A personalized comfort sensor networks with a wireless communication system can be facilitated with IoT.


Thank You!
The Hong Kong University of Science and Technology