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# Experimental Application of PIV: Micro-Scale Room Turbulence (Surgical micro-environment turbulent airflows) and Thermal Comfort Measurements

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CBT 3, January 19-22, 2026, KTH, Sweden

Acknowledgement: Kunal Bairwa at EPT NTNU

HumanIC project has received funding from the European Union’s Horizon Europe research and innovation program under the Marie Sklodowska-Curie (HORIZON-MSCA-2022-DN-01, project no 101119726

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# Table of content



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# Background

- **High mortality rate in operating rooms**
  - The 3rd highest cause of mortality in the world.
  - Surgical site infection occurs in 2% to 10% of all patients undergoing inpatient surgical procedures.

- **Very high indoor air quality requirements**
  - 10-100 CFU/m$^3$ in operating rooms
  - Ref. 1000-5000 CFU/m$^3$ in residential buildings

- **More complains from surgical staff (PPD>75%) and patients on indoor thermal environment quality during operation!**

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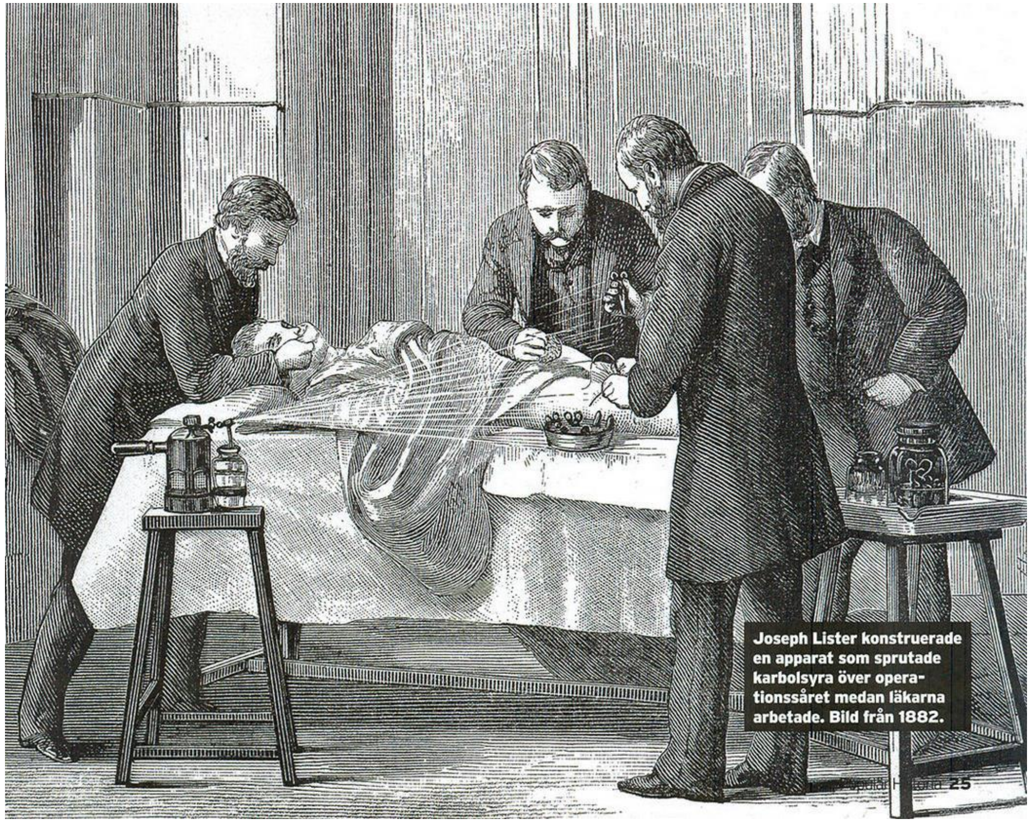
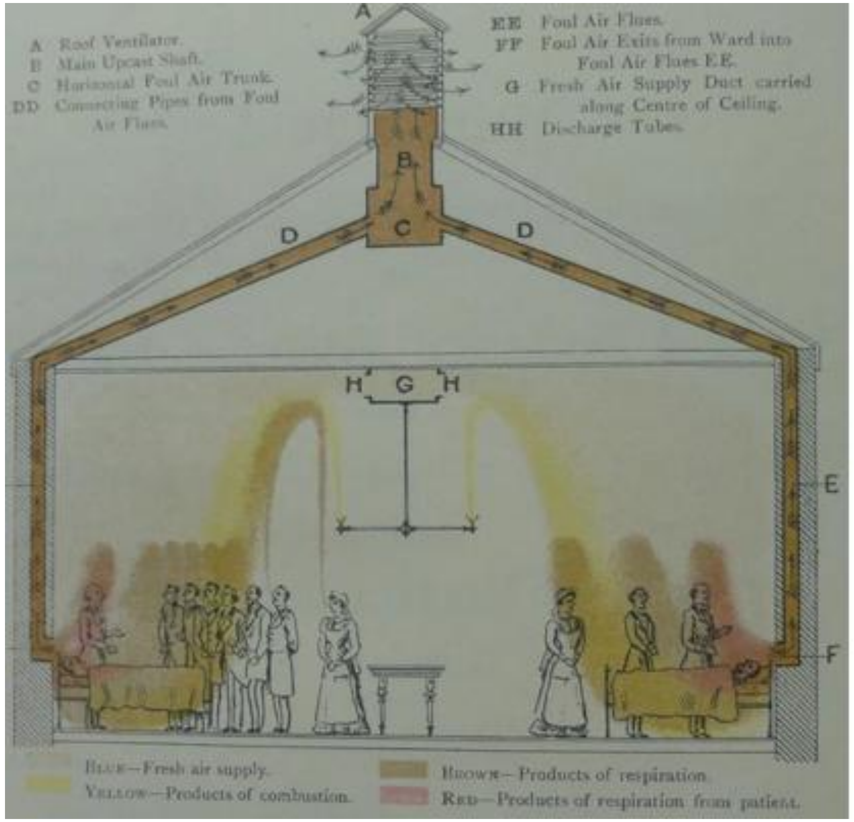
# 100 years ago...

1882 Joseph Lister – Phenol (fenol, karbolsyre)




1899 Robert Boyle & Son

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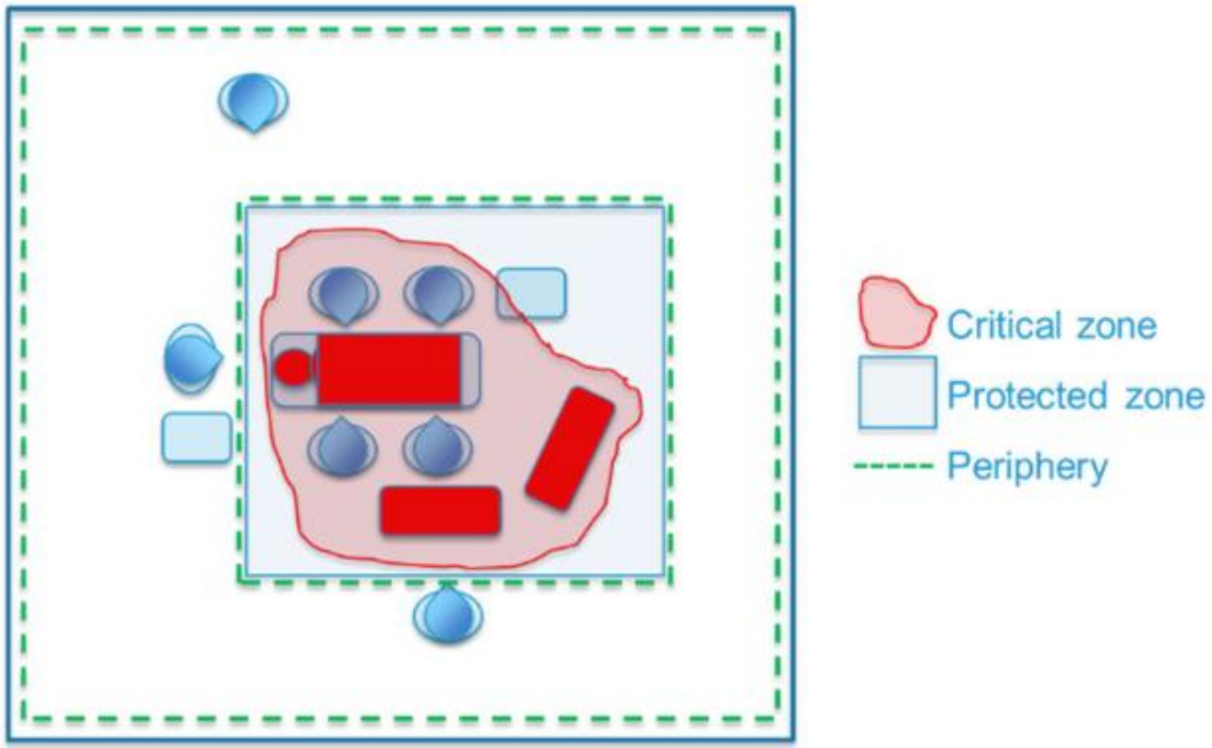
# **Critical zone** - EU TC156/W18 - R3 Nordic Guideline for Hospital Ventilation - General Requirements, Operating Suites, and Isolation Rooms (20.9.2023)

**OR with Protected Zone principle**



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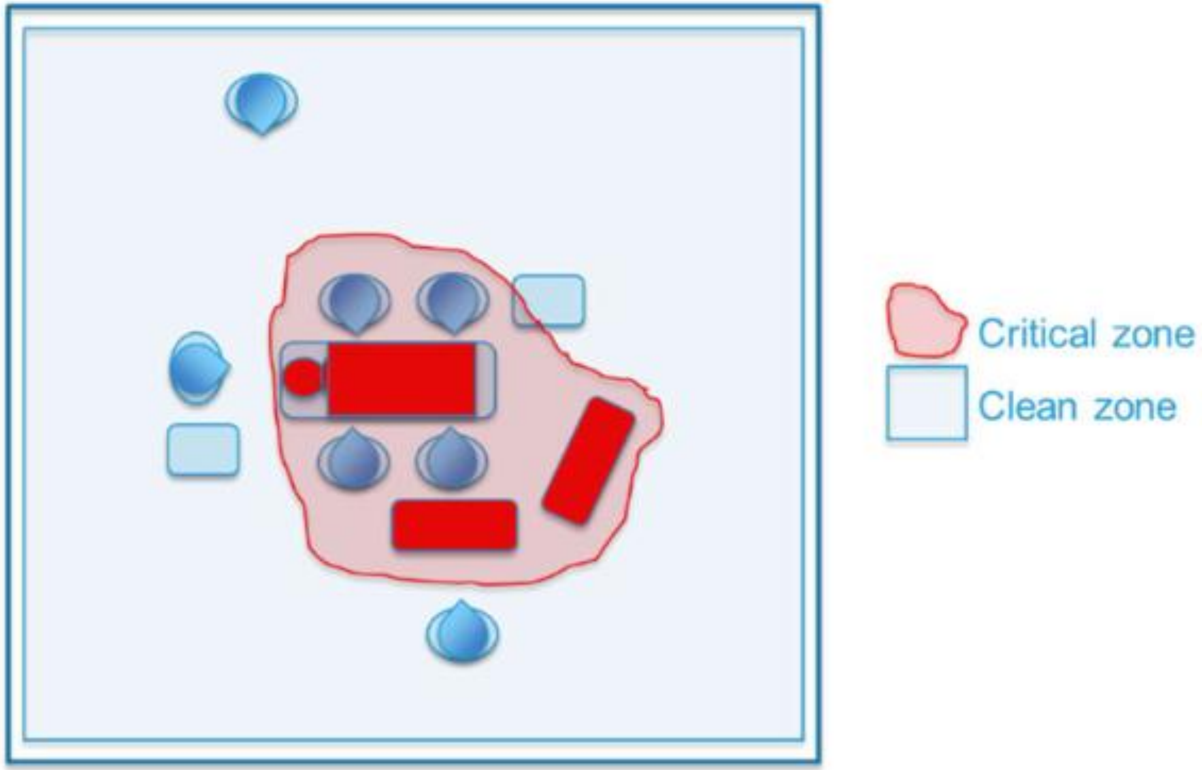
# **Critical zone** - EU TC156/W18 - R3 Nordic Guideline for Hospital Ventilation - General Requirements, Operating Suites, and Isolation Rooms (20.9.3023)

**OR with Dilution mixing principle**



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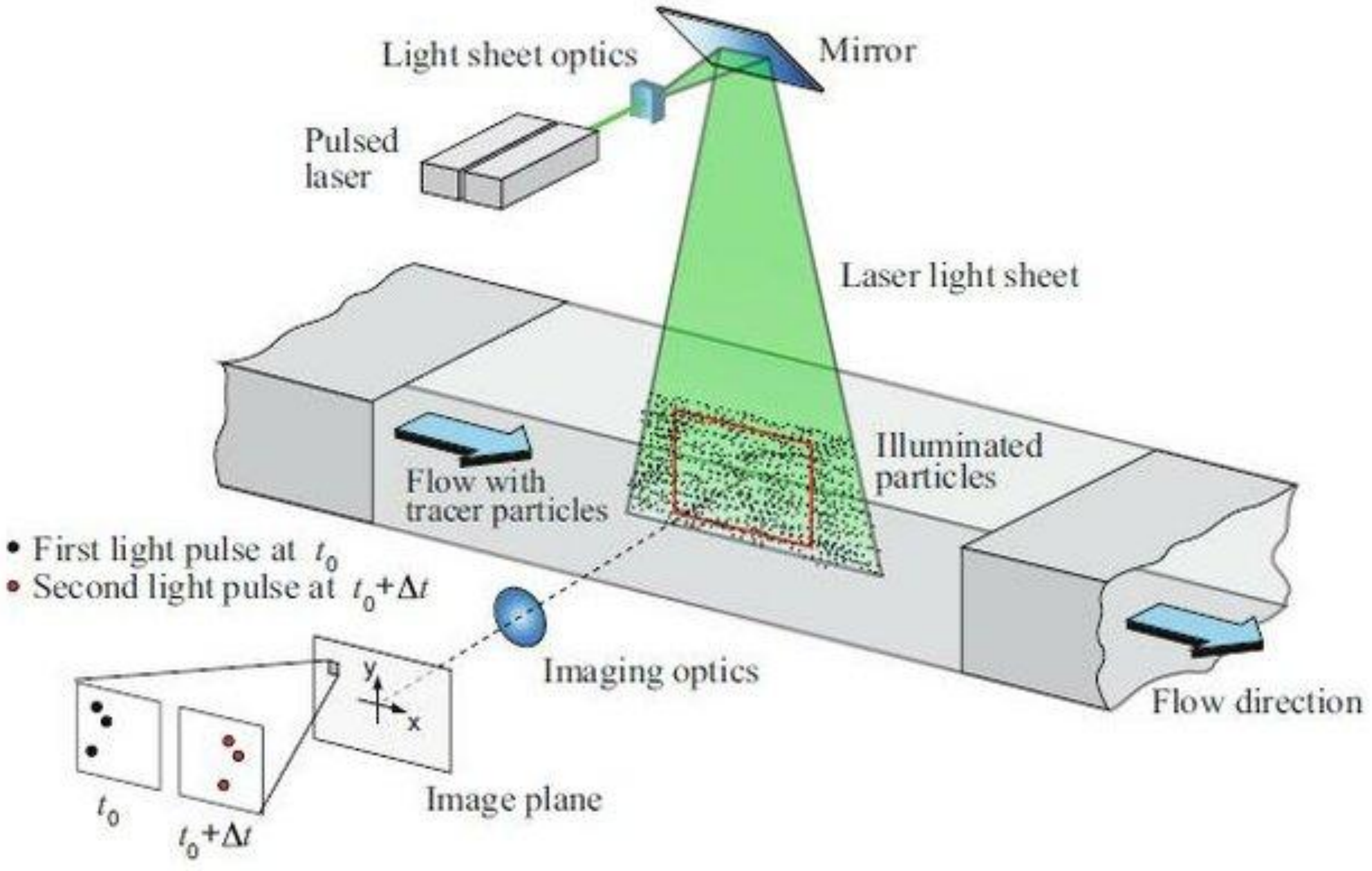
# Typical 2D–2C PIV System Components

A conventional 2D–2C PIV systen includes a Nd:YAG laser, high-resolution CCD camera, and software for cross-correlation analysis, enabling precise measurements of airflow characteristics in surgical environments.




Experimental arrangement for planar 2C-2D PIV

https://www.researchgate.net/profile/Florencia-Renteria-Del-Toro/publication/358191843/figure/fig1/AS:1117365634904064@1643412135397/Experimental-arrangement-for-planar-2C-2D-PIV_W640.jpg

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# Experimental Applications of PIV
# Part I

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# The OR LAB at NTNU

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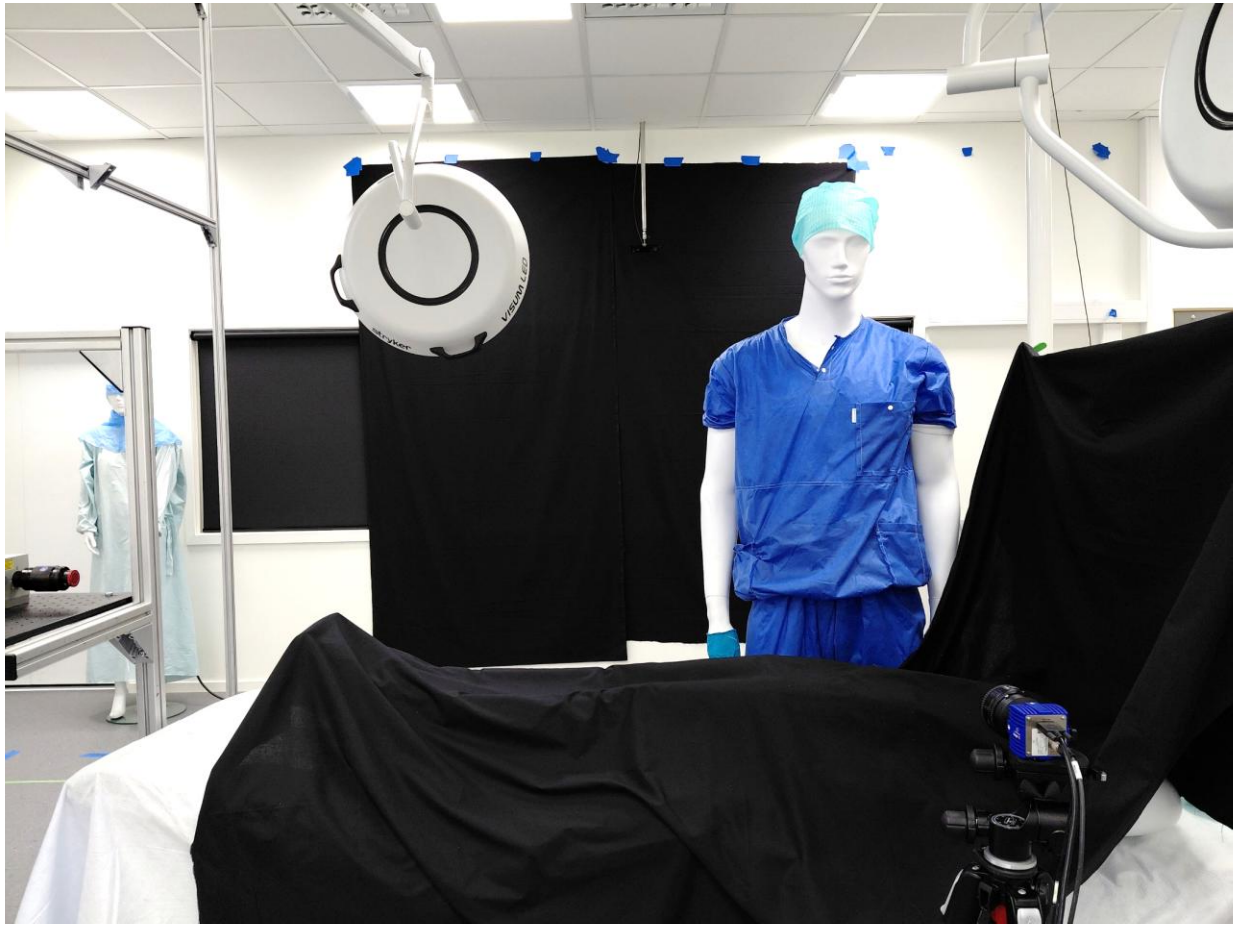
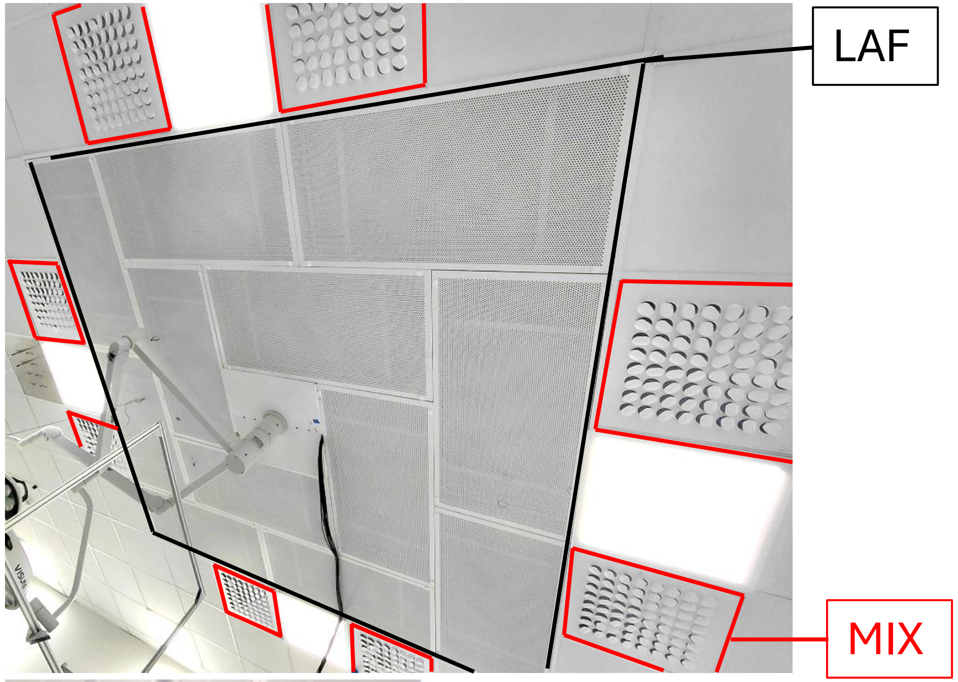
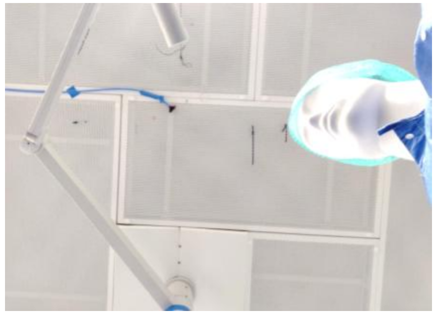
# PIV application in the OR LAB at NTNU

## Steady State Conditions - Setup for test cases





| Ventilation Mode | Flow rate (m^3/h) | ACH |
|---|---|---|
| Mix | 3800 | 20 |
| LAF Low | 9950 | 52 |
| LAF Medium | 11871 | 62 |
| LAF High | 14530 | 76 |

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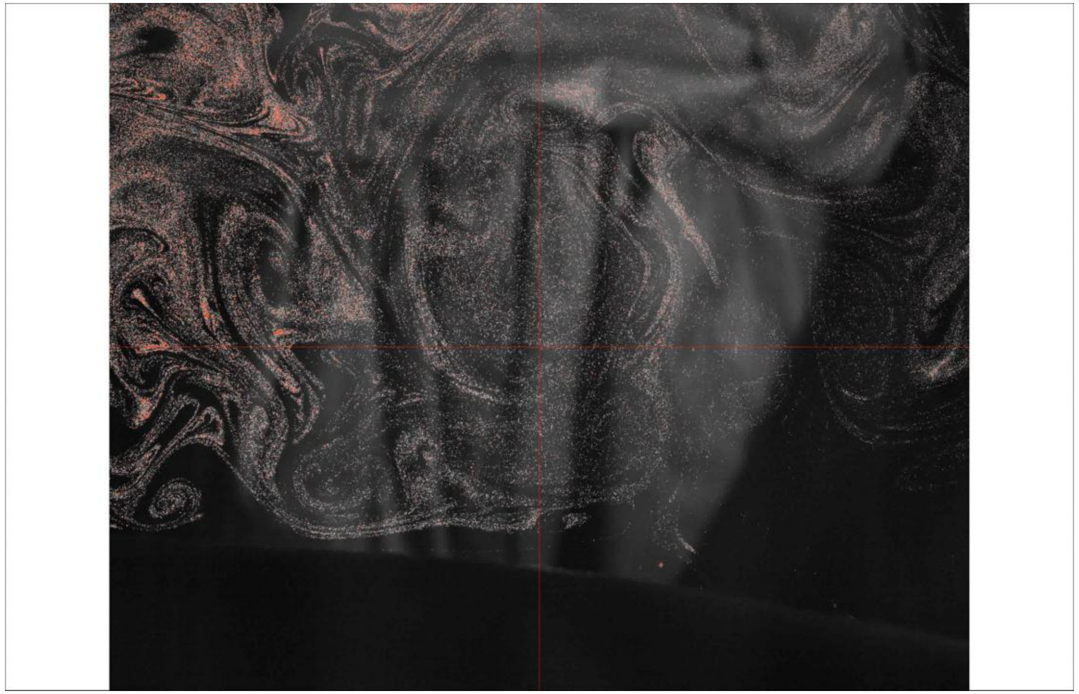
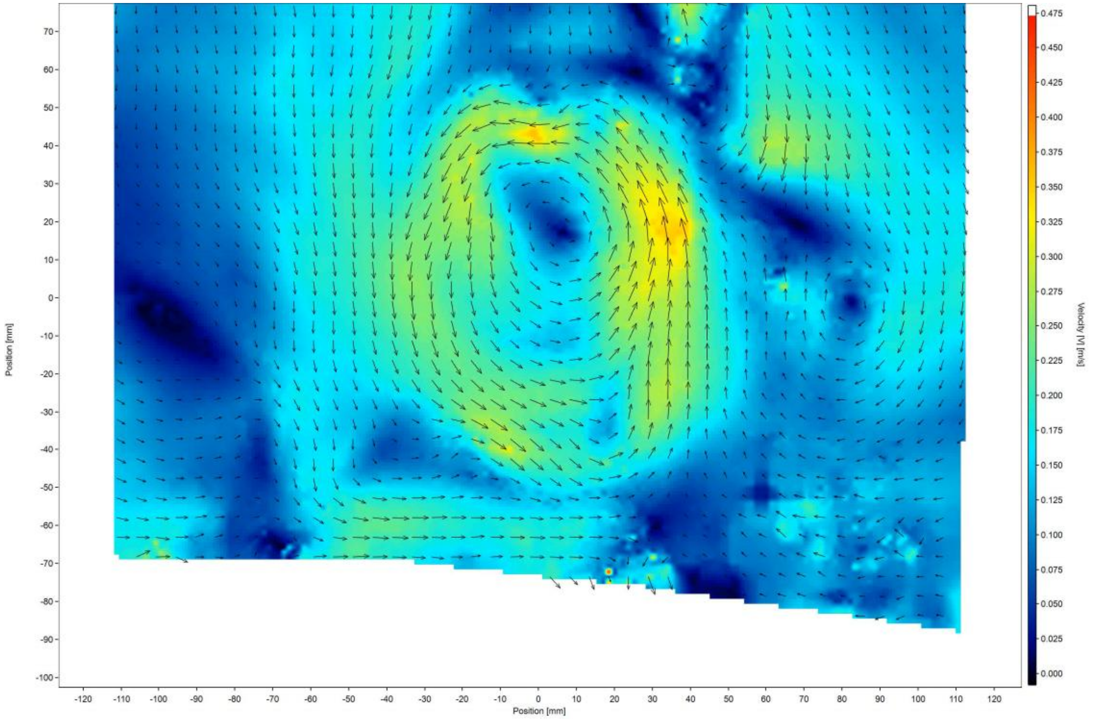
# Initial data processing

## LAF High : PIV with surgeon

### Raw PIV



### Velocity field

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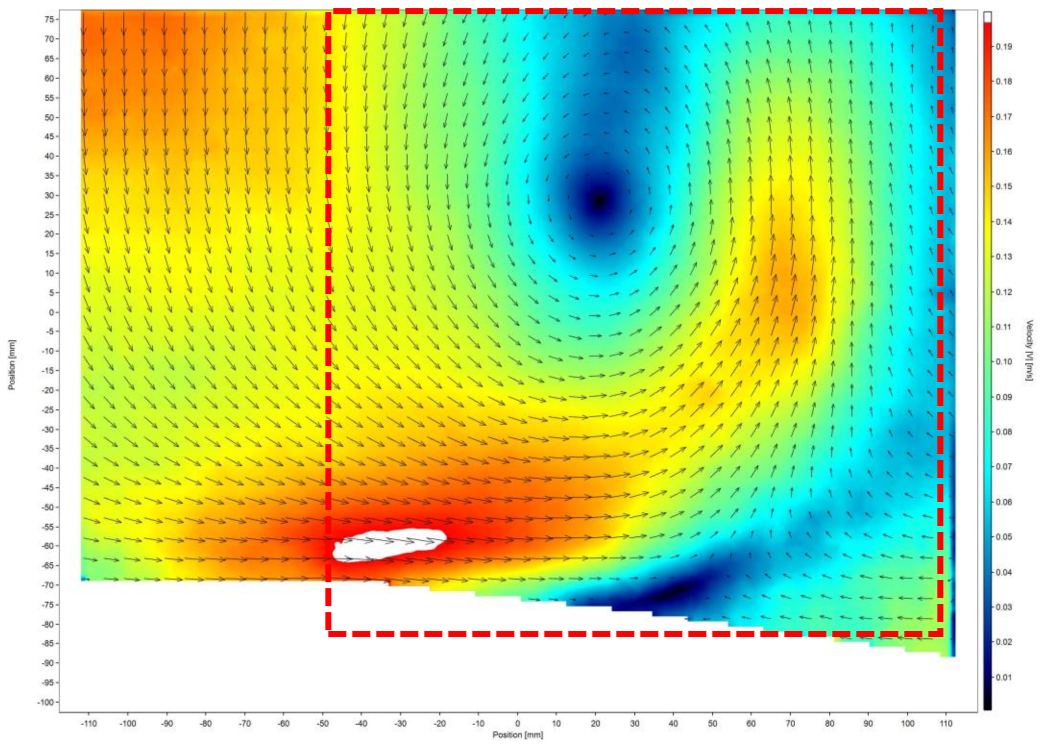
# Initial data processing

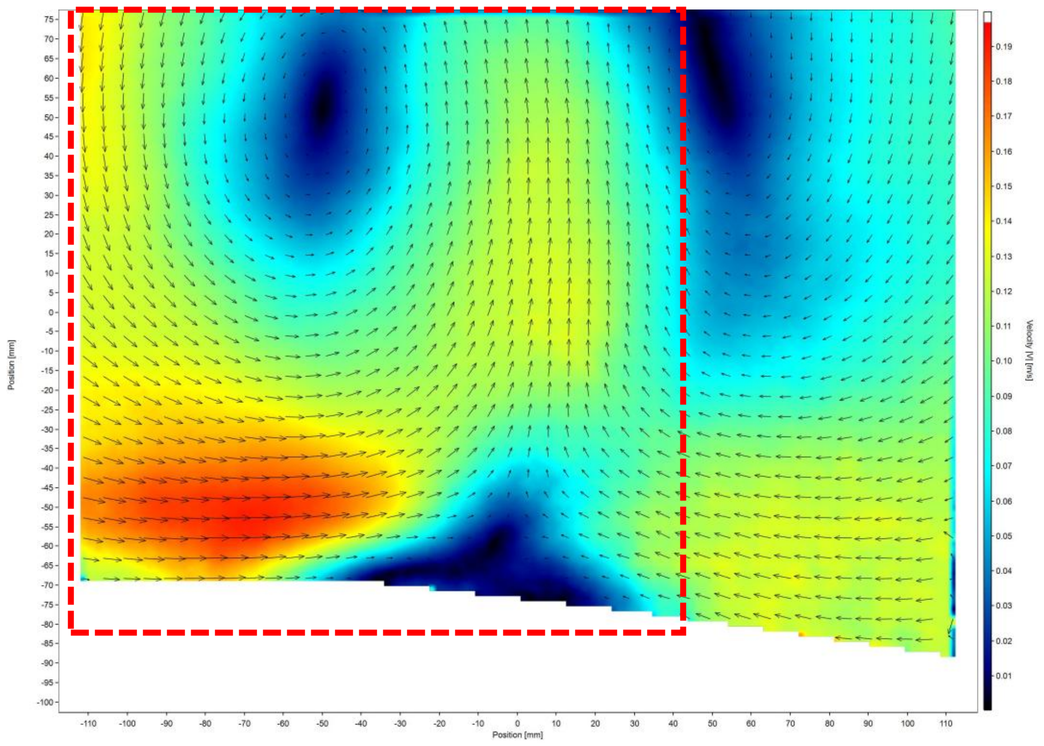
HumanIC

## LAF High : Velocity comparison

**With surgeon**




**Without surgeon**

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# Initial data processing

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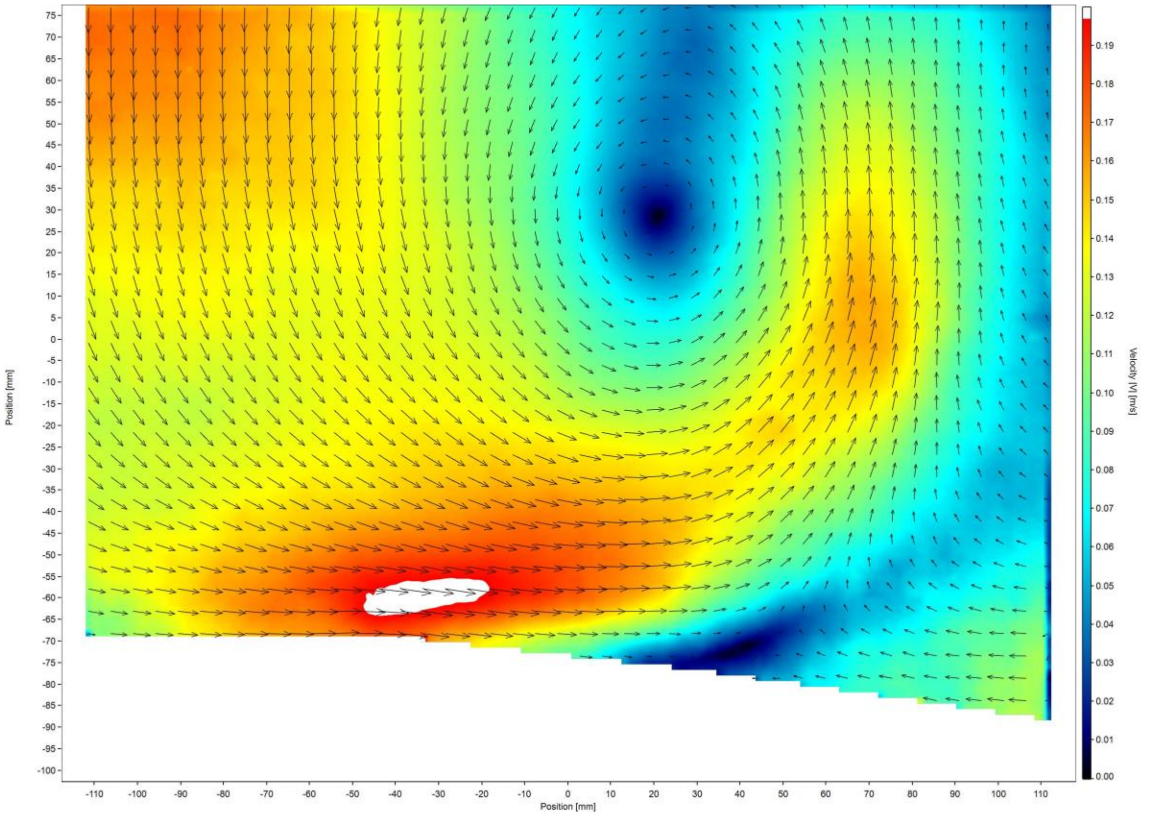
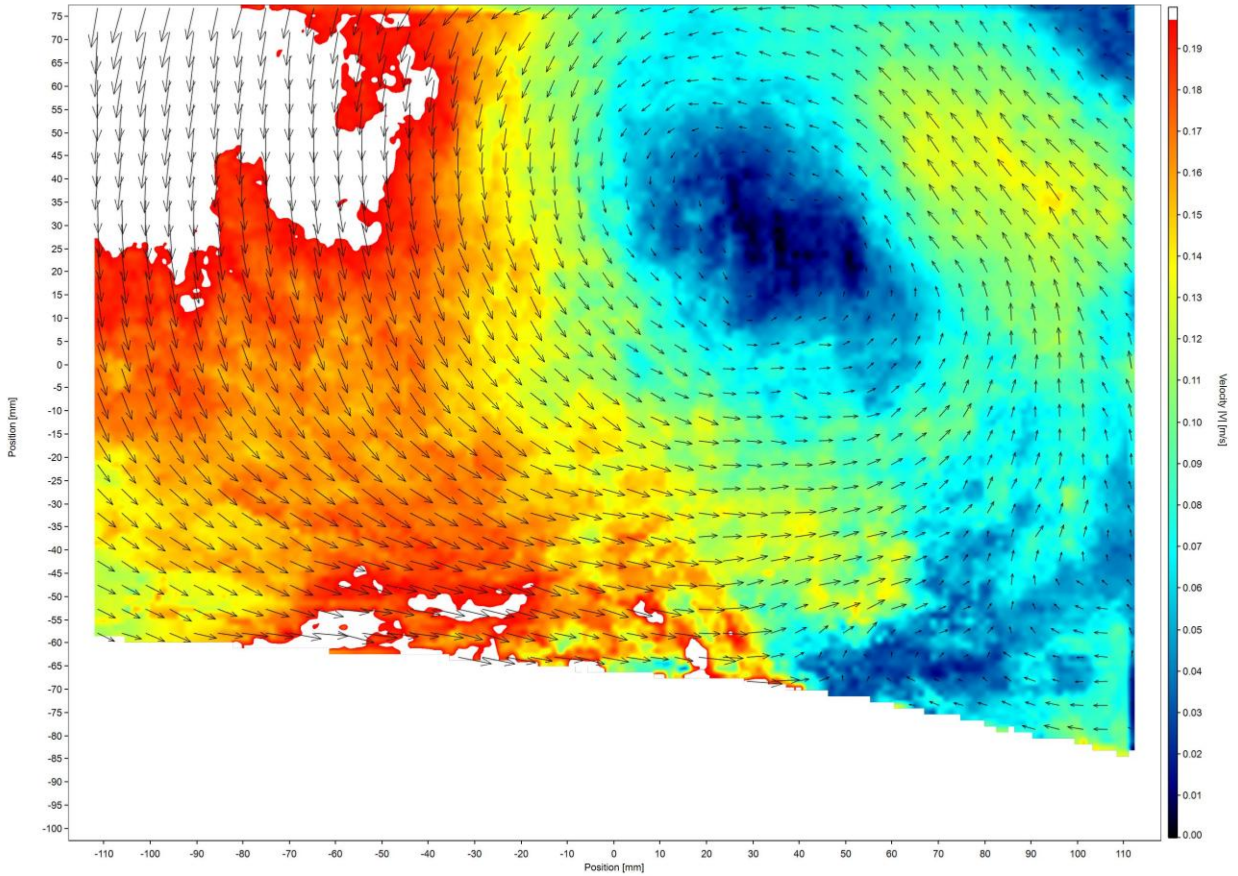
## LAF High : With surgeon

### No thermal plumes




### Thermal plumes





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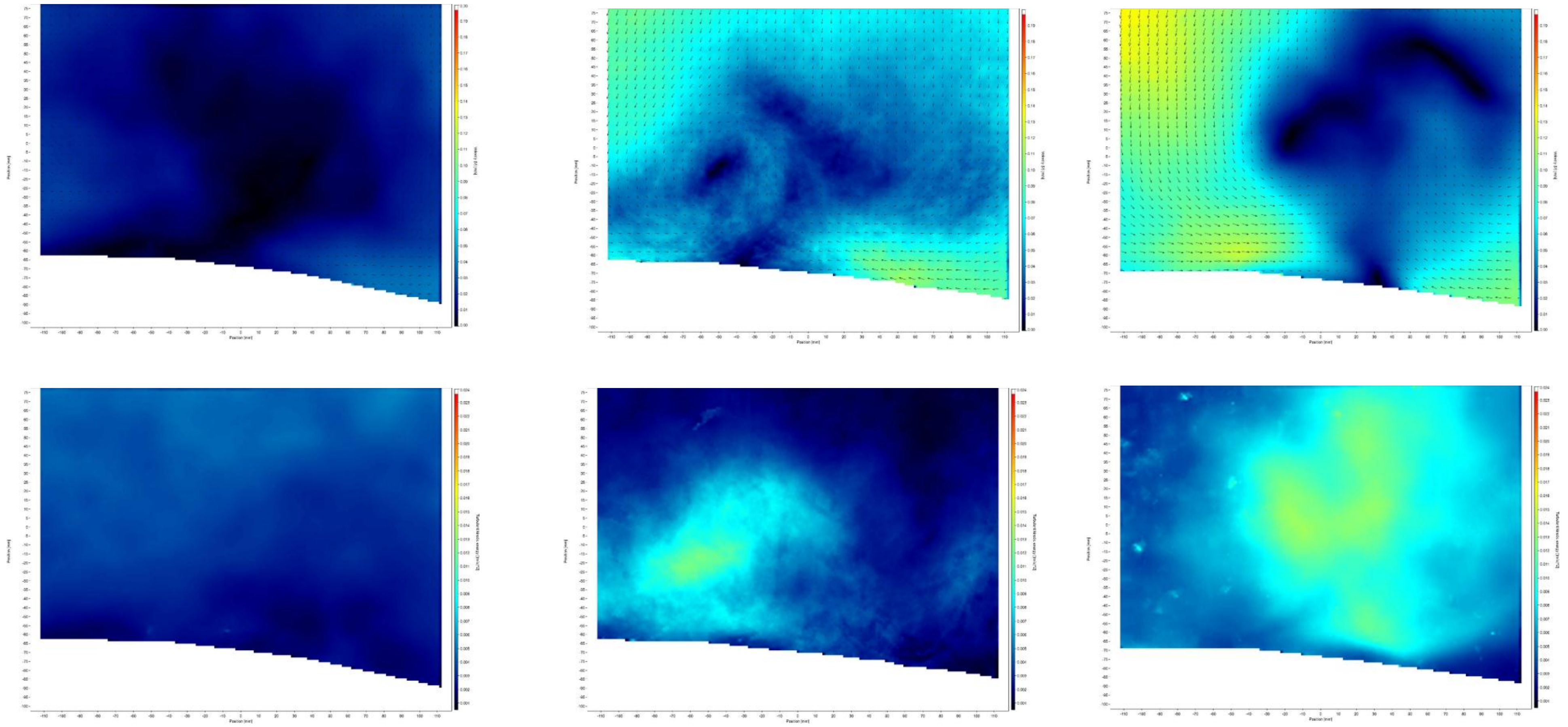
# Initial data processing

## With surgeon

Mix | LAF Low | LAF Med.

Velocity

Turbulent kinetic energy



HumanIC

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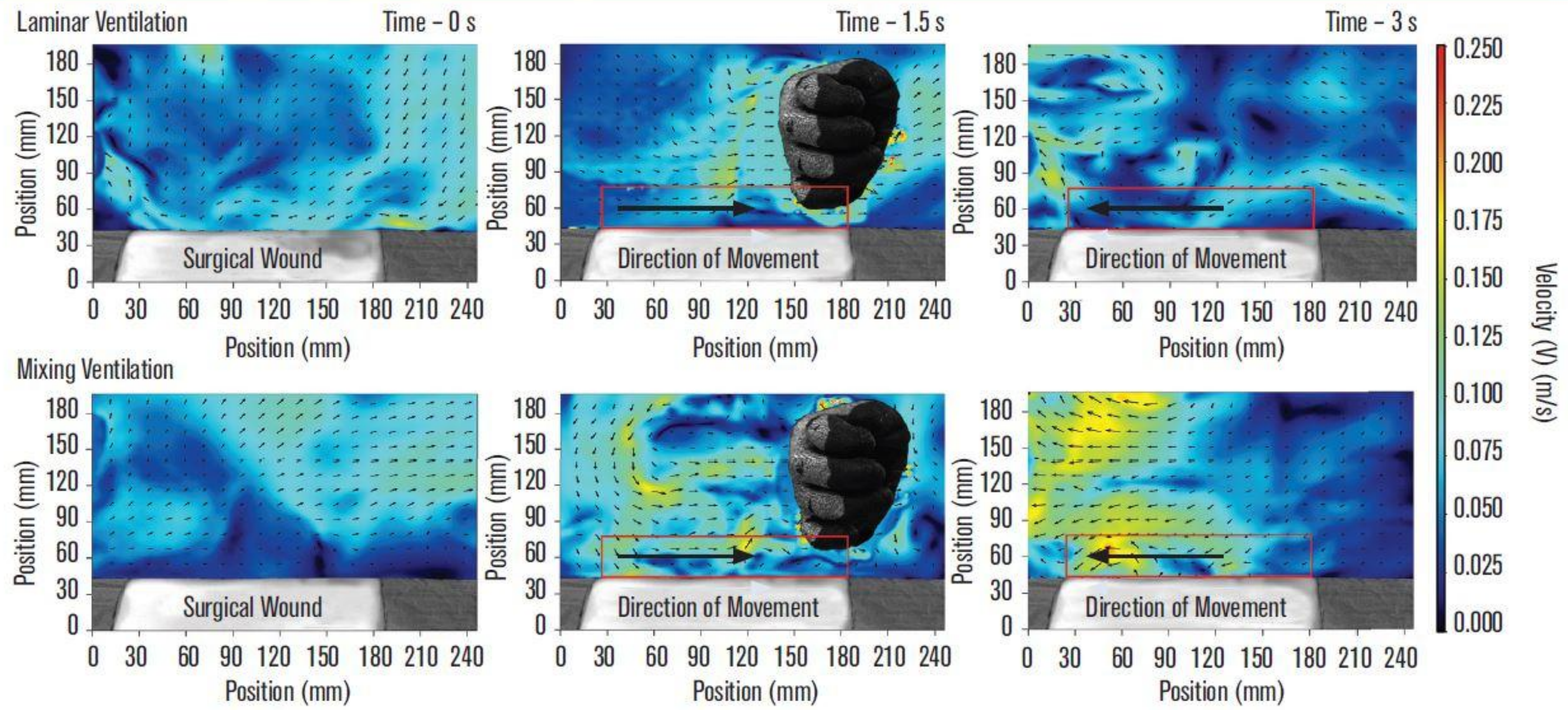
# PIV application for surgical micro environment in the OR LAB at NTNU – Transient Condition

Laboratory Research On Airborne Infection Control in Hospital Operating Rooms. ASHRAE Journal 2025 May

**FIGURE 5** Flow structure in the vicinity of the surgical wound in the case of LAF and MV ventilation. The velocity field measured at 0 s just before the start of the surgeon's arm movement in the horizontal direction, 1.5 s after the arm has moved 120 mm (0.394 ft) and after 3 s when the arm has moved back to the same position (120 mm [0.394 ft]) after reaching 240 mm (0.787 ft) are shown.

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# Experimental Applications of PIV
# Part II

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# Experimental Investigation of Operating Room Air Distribution in a Full-Scale Laboratory Chamber Using Particle Image Velocimetry and Flow Visualization

http://dx.doi.org/10.4236/jfcmv.2013.11005

Table 1. Laboratory chamber characteristics.

| Parameter Range | Value |
|---|---|
| Diffuser array dimensions | 2.44 × 3.05 m |
| Diffuser face area | 7.06 $m^2$ |
| ACH | 31.6 |
| Nominal face velocity | 0.127 $m^3/s\text{-}m^2$ |
| Room air temperature | 20˚C |
| Supply air temperature | 18.3˚C |
| Room pressurization | +2.5 Pa |

http://dx.doi.org/10.4236/jfcmv.2013.11005

James McNeill, Jean Hertzberg, Zhiqiang Zhai, Experimental Investigation using PIV and Flow Visualization

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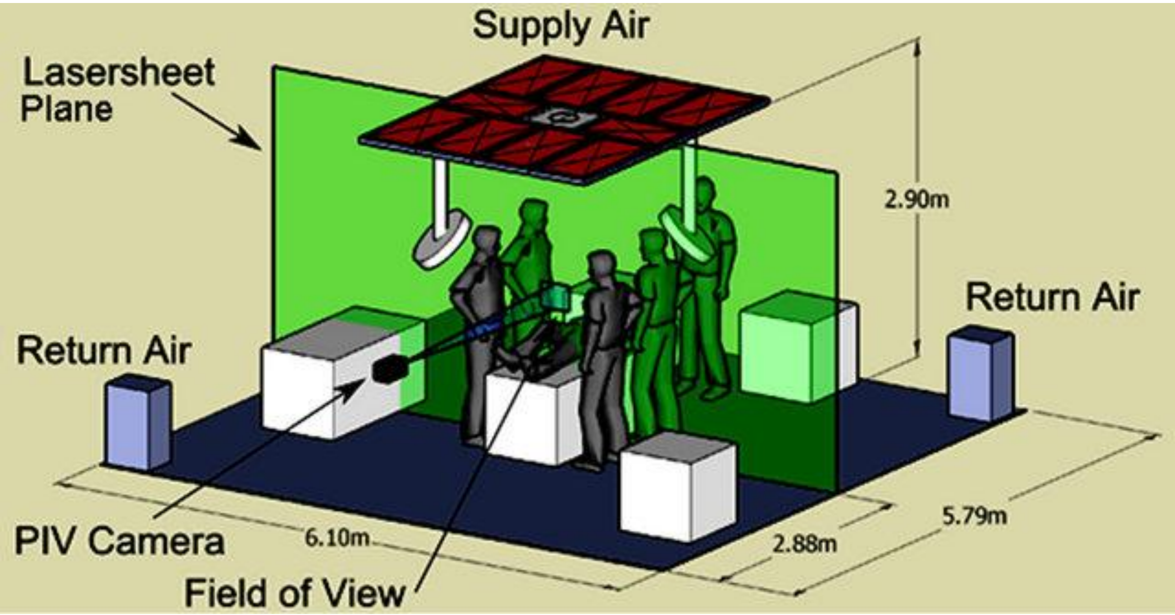
# Experimental setup of the PIV system in a Full-Scale Laboratory Chamber




http://dx.doi.org/10.4236/jfcmv.2013.11005

The fog droplets have diameters on the order of 1 μm.

It was injected at the air handling unit in order to achieve neutral buoyancy and well-mixed conditions at the diffuser outlet.

The PIV measurements were captured in a two-dimensional plane across the surgical site of the patient using a camera mounted normal to the laser sheet.

http://dx.doi.org/10.4236/jfcmv.2013.11005

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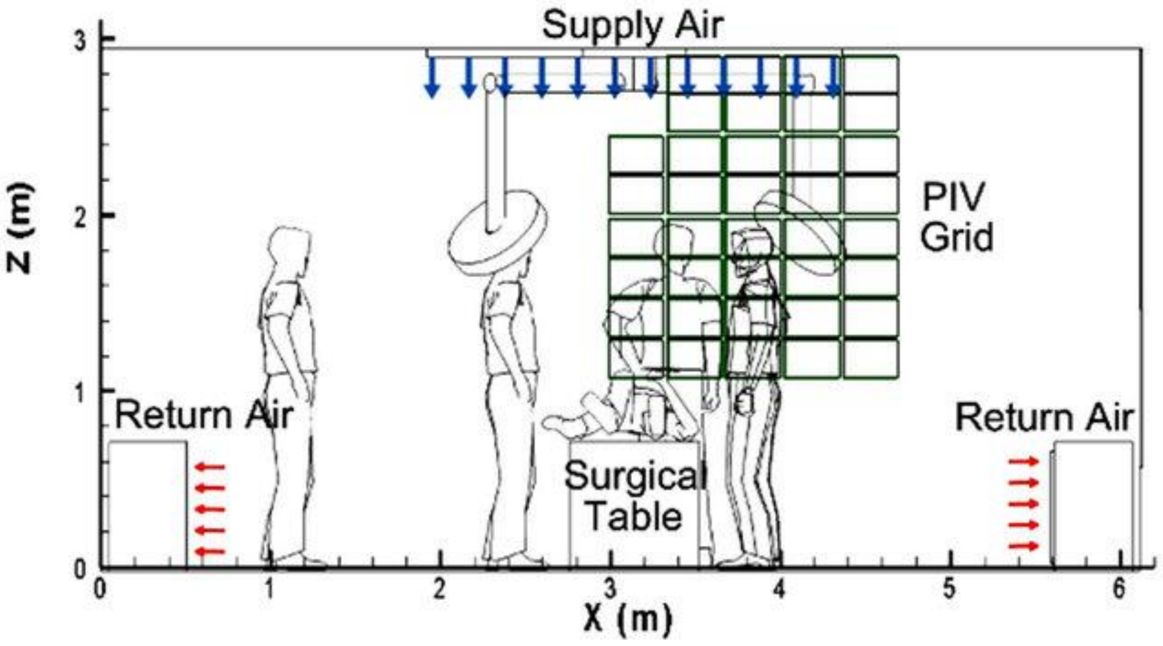
# Experimental setup of the PIV system in a Full-Scale Laboratory Chamber




http://dx.doi.org/10.4236/jfcmv.2013.11005

The images were separated by 4000 μs between frames. A standard Nyquist grid was used with a central difference offset scheme and a correlation window spot size of 128 × 128 pixels.
The image pair correlation was calculated using a fast Fourier transform (FFT) algorithm, and sub-pixel accuracy was provided with a Gaussian fit.
The laser sheet was approximately 5 - 6 mm thick in the field of view region in order to reduce the quantity of through-plane particles that contribute to particle dropout.

http://dx.doi.org/10.4236/jfcmv.2013.11005

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# Measurement Results of Particle Image Velocimetry

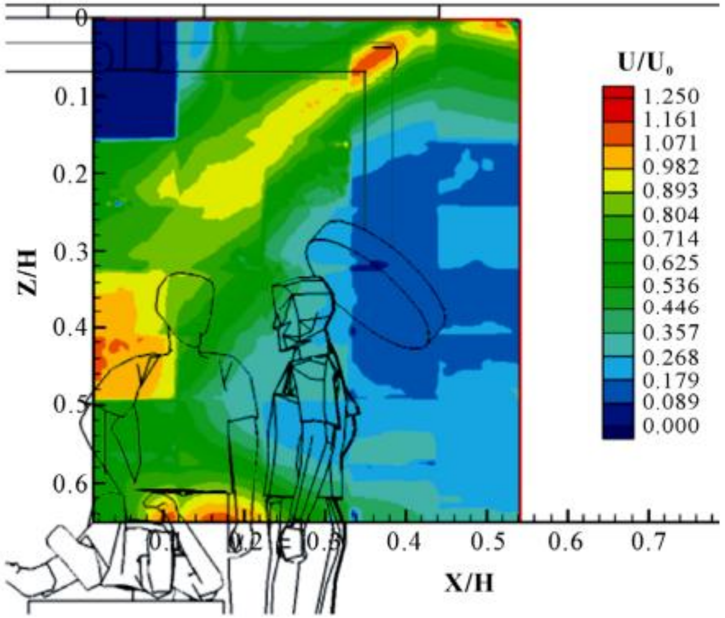


**Figure 10. Normalized velocity magnitude contours in the plane intersecting the center of the room in the sterile region above the patient.**

http://dx.doi.org/10.4236/jfcmv.2013.11005

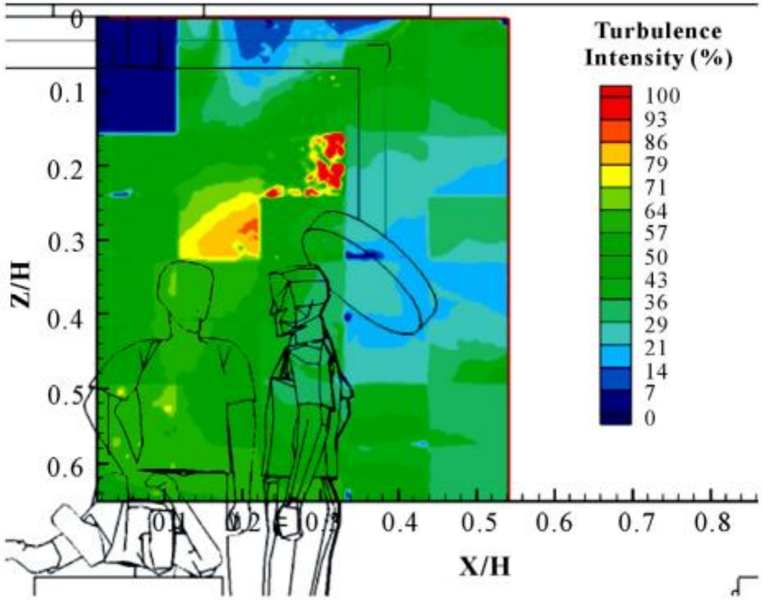


**Figure 12. Turbulence intensity contours in the plane intersecting the center of the room in the sterile region above the patient.**

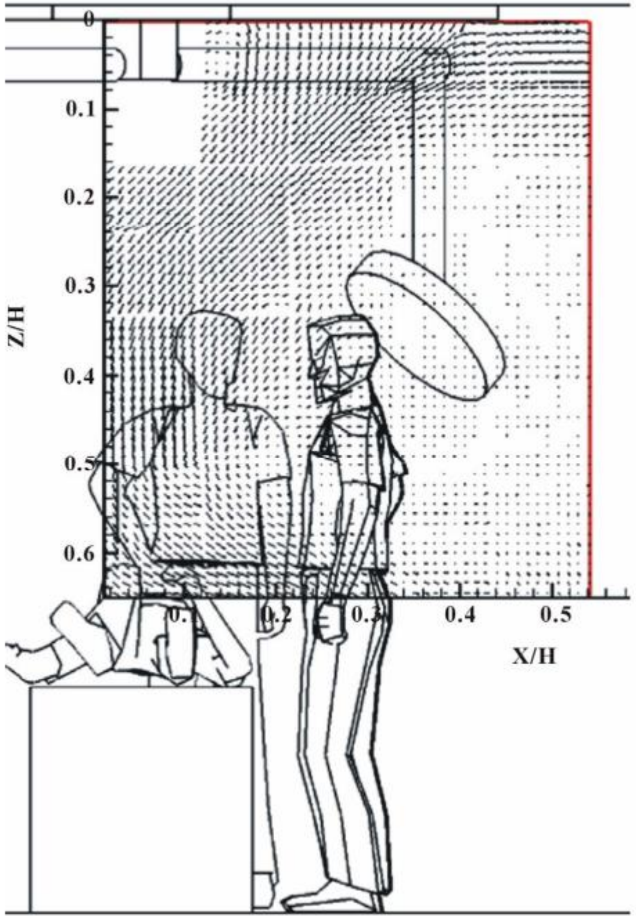


**Figure 9. Velocity vectors in the plane intersecting the center of the room in the sterile region above the patient.**

http://dx.doi.org/10.4236/jfcmv.2013.11005

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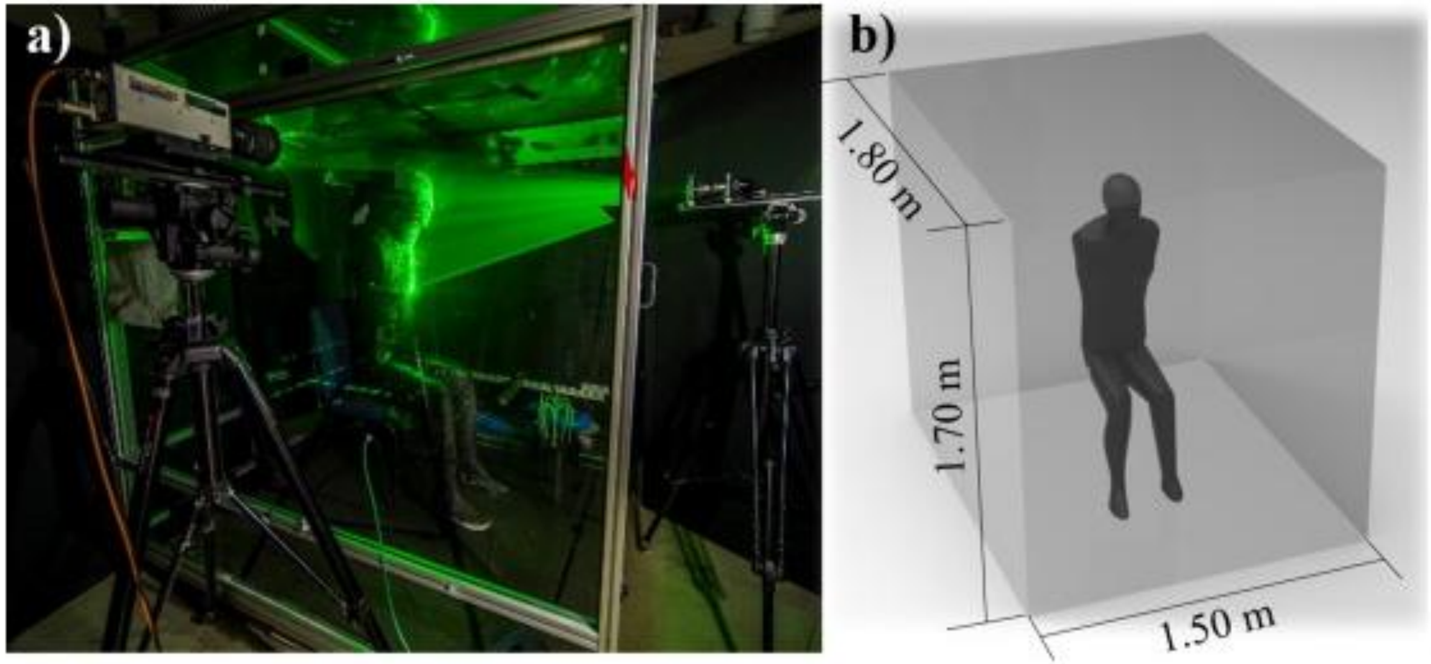
# Thermal Plume Interactions in Surgical Environments

## BUOYANT AIRFLOW DYNAMICS

Buoyant plumes from patients and staff interact with surgical lamps, creating complex airflow patterns that affect overall environment behavior.




https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.138

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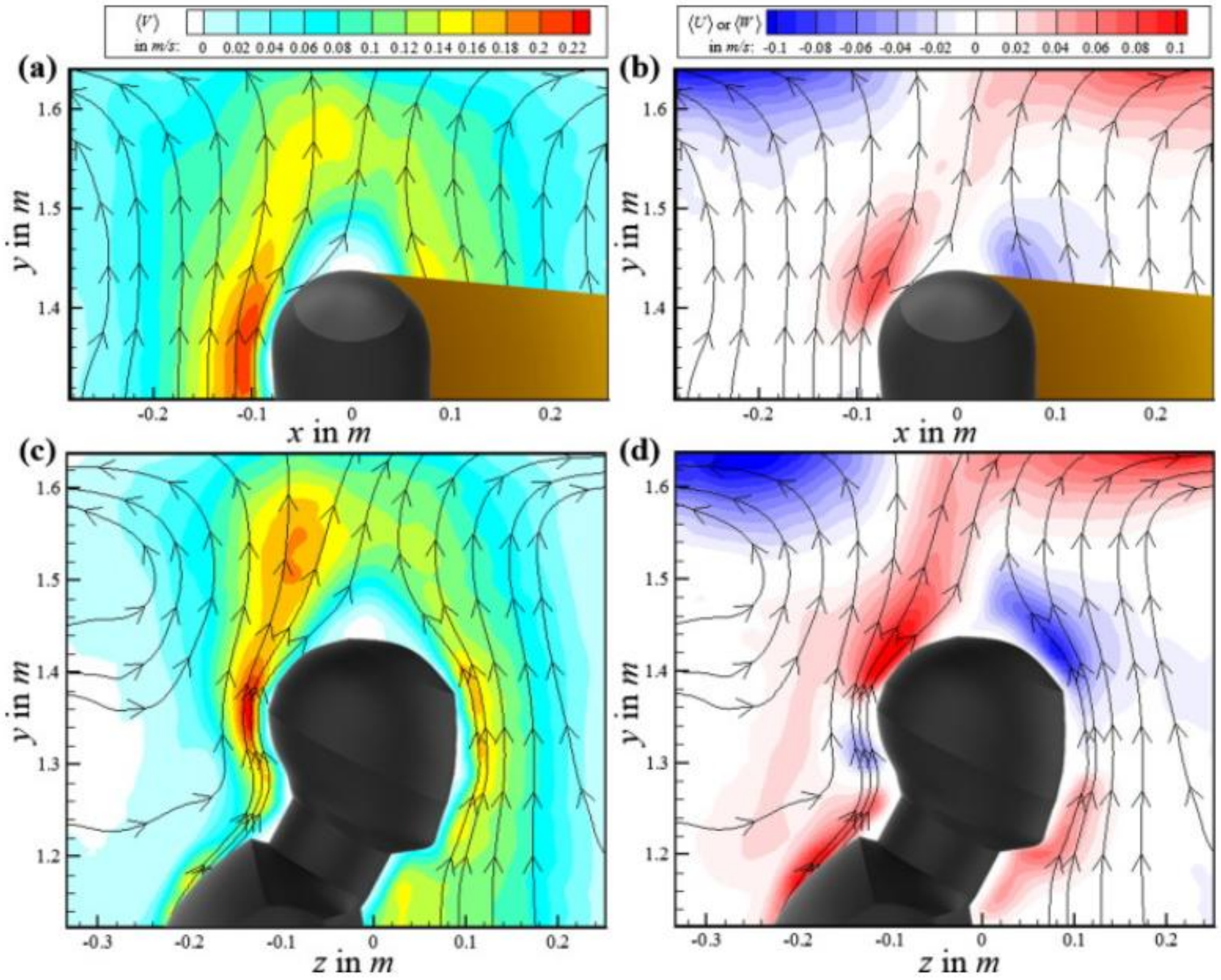
# Thermal Plume Interactions in Surgical Environments

## BUOYANT AIRFLOW DYNAMICS

Buoyant plumes from patients and staff interact with surgical lamps, creating complex airflow patterns that affect overall environment behavior.




Time-averaged airflow distributions in (a) & (b) coronal plane and (c) & (d) sagittal plane.
https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.138

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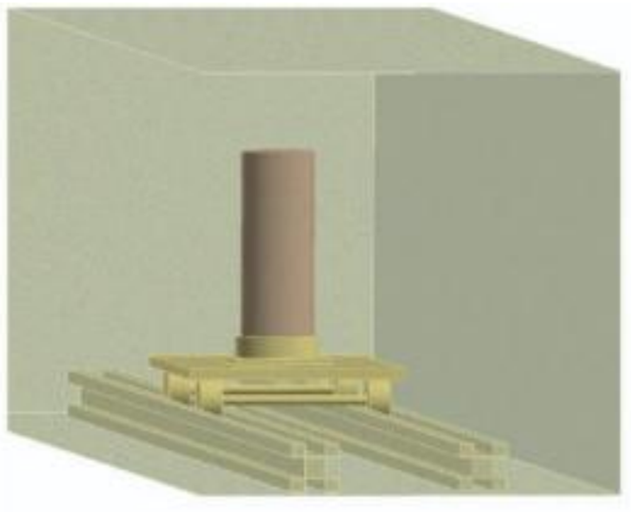
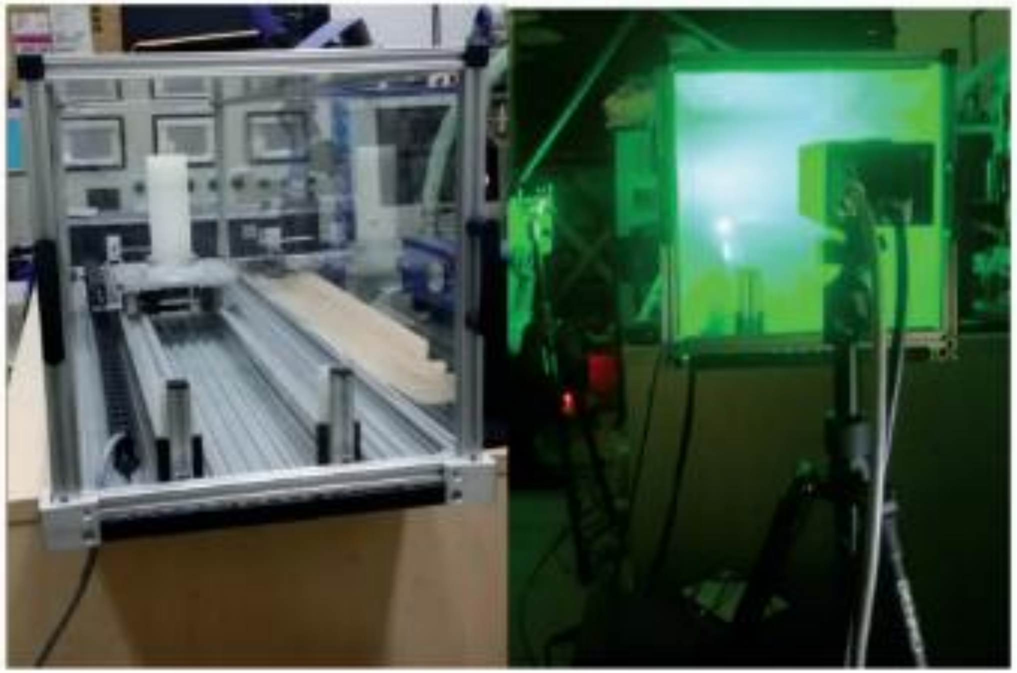
# Human-walking-induced wake flow – PIV experiments and CFD simulations (Wake Formation and Its Impact on Airflow)

Velocity change and increased turbulence can significantly elevate contamination risks, highlighting the need for strategic airflow design in surgical settings.





The small-scale test chamber (left) and the experimental imaging set-up (right)

https://doi.org/10.1177/1420326X17701279?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

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# Key findings

It revealed an upward air vortex and a strong downward airflow behind the moving body along the vertical centreline.

During the movement, the wake airflow fields behind the object were gradually affected, forming a downward airflow and an upward air vortex, and eventually replaced by a stable horizontal airflow.

It also showed a strong downward and expansive air vortex in the wake flow from the top corners of the moving object to the floor.

It illustrated that, the contaminant released from the human body would converge and then rapidly approach the floor, disperse to the surrounding region.

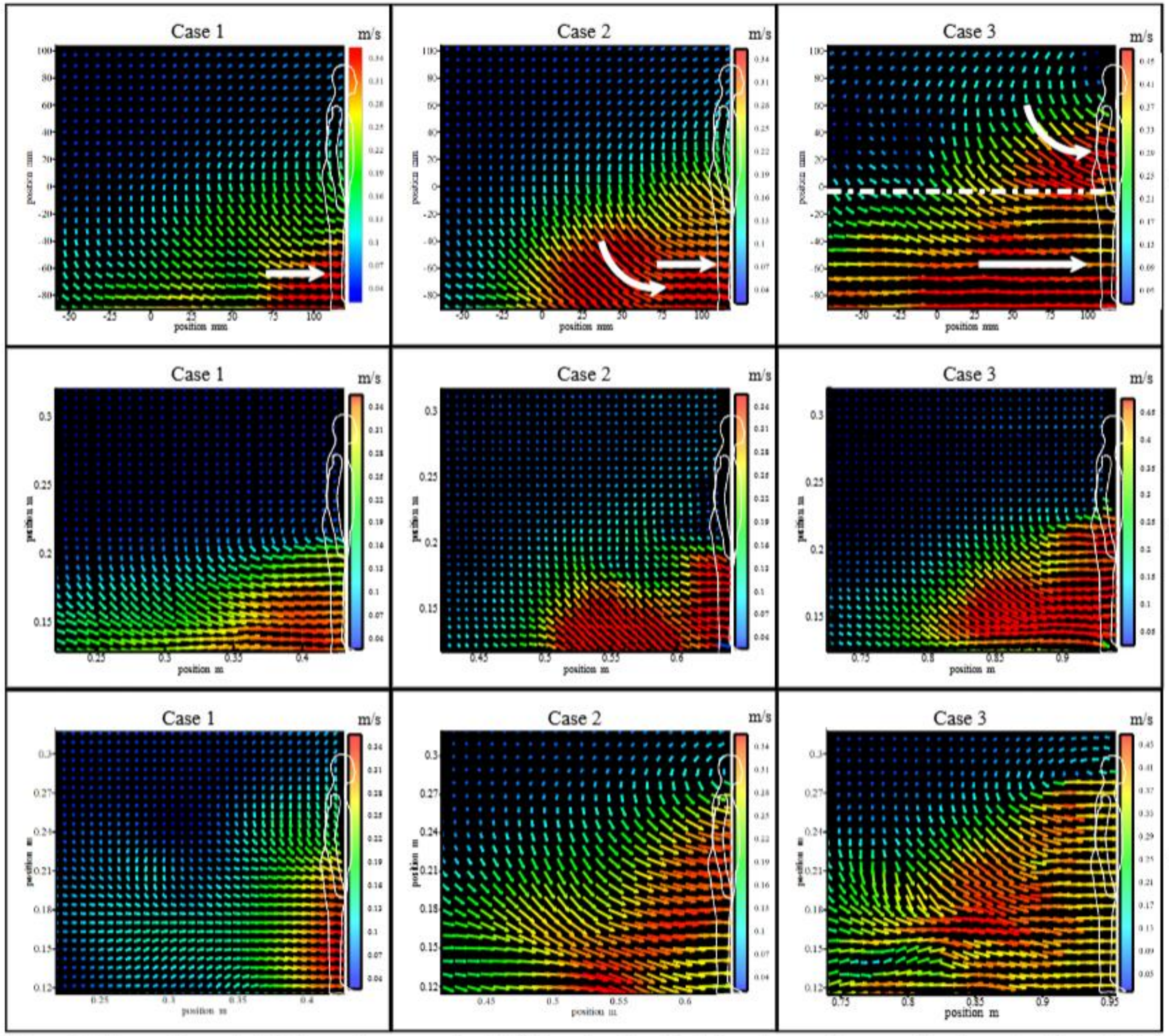


**Fig. 6.** Experimental (a) and numerical (b) velocity fields along the vertical centerline behind the moving manikin under the speed of 0.5m/s at Cases 1, 2 and 3

https://doi.org/10.1177/1420326X17701279?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

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# Discussions

**Whether PIV may be used in your own project?**

**What may be challenges using PIV in your project?**

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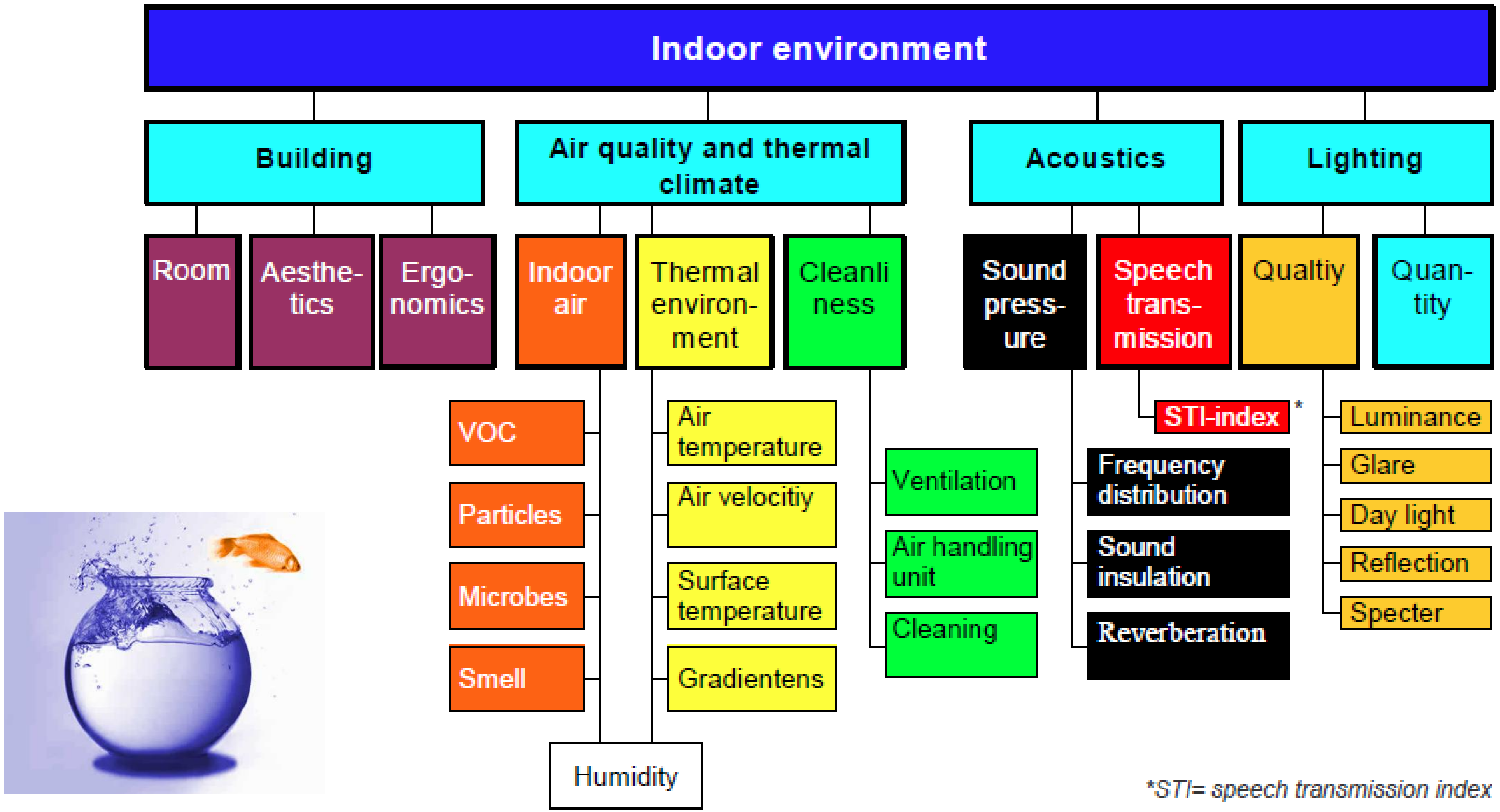
# Thermal Comfort Measurement

# Dimensions of the indoor environment




Ref. REHVA Guide book NO. 6

*STI= speech transmission index

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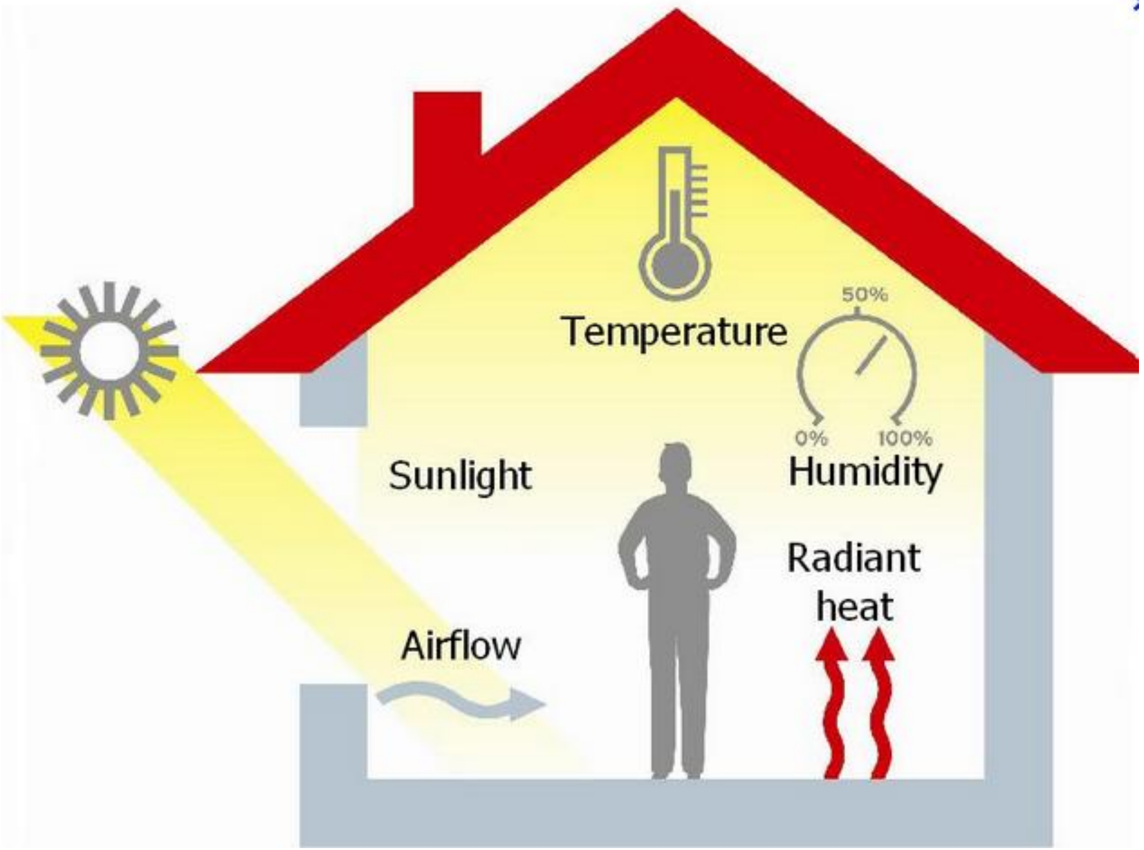
# Thermal environment and thermal comfort

**Thermal comfort**: '...that condition of mind which expresses satisfaction with the thermal environment'

(NS-EN ISO 7730)

**What will affect human thermal comfort?**




https://atjenese.wordpress.com/2012/05/04/the-assessment-of-thermal-comfort-of-living-environment-in-tsunami-disaster-place/



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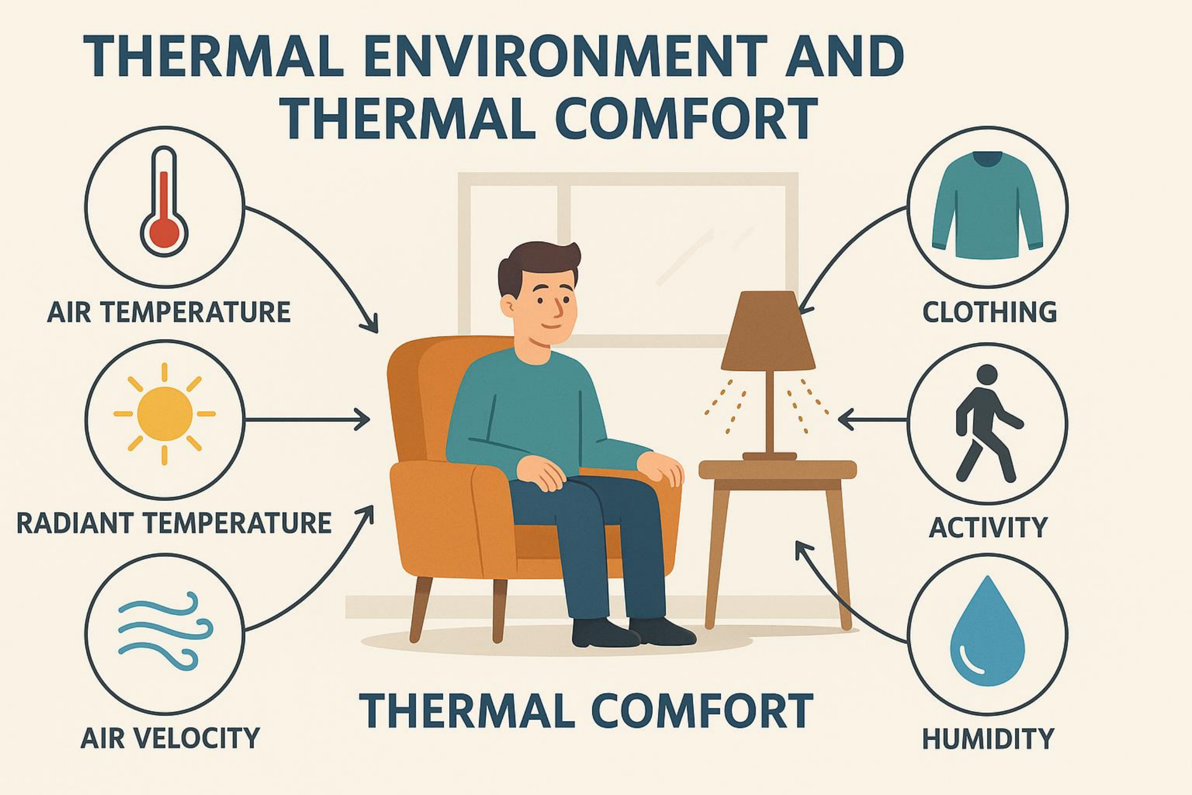
# Thermal comfort – basic parameters

- Human related parameters:
  - **Metobolic rate**
  - **Isolation level (clothing)**
- Basic parameters that determine the t
  - **air temperature**
    - Dry bulb temperature
    - Wet bulb temperature
  - **radiant temperature**
    - Mean radiant temperature
  - **air velocity** (mean and turbulence intensity)
  - **relative humidity** (water vapour partial pressure)

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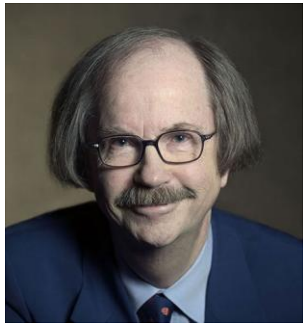
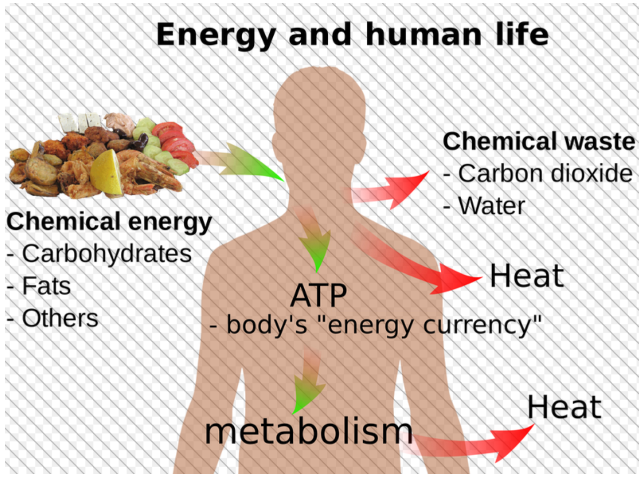
# Modelling of thermal comfort - Heat exchange method

- Metabolic Rate M
  - Degree of muscular activities
  - Environmental conditions
  - Body size
- Heat loss Q
  - Respiration
  - Convection
  - Radiation
  - Conduction
  - Evaporation
- Body thermal balance equation
  - M=Q comfort
  - M<Q cold
  - M>Q hot



Professor P.O. Fanger
July 16, 1934 – September 20, 2006




http://en.wikipedia.org/wiki/Energy

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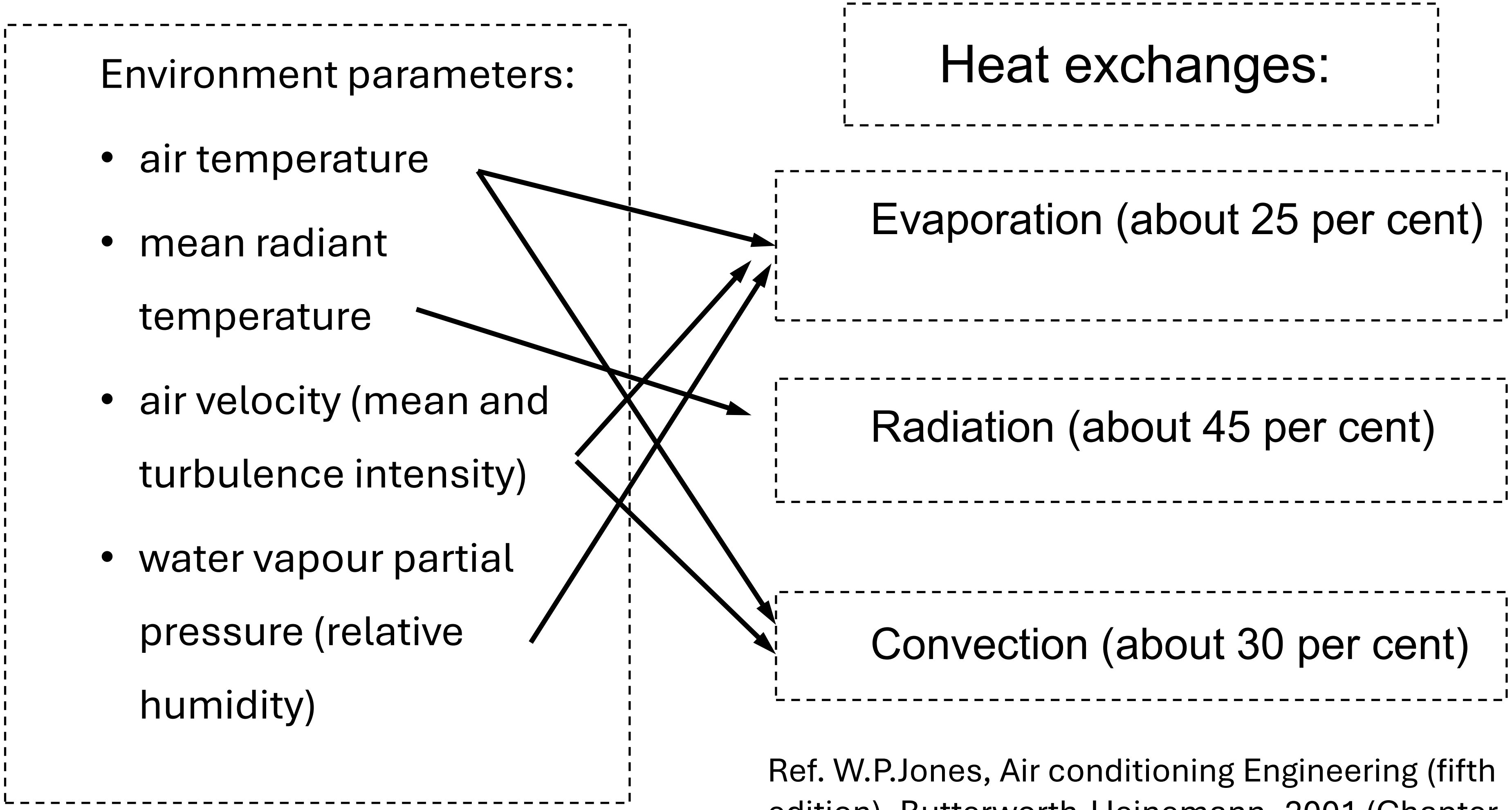
# Interaction of human body with the thermal environment




Ref. W.P.Jones, Air conditioning Engineering (fifth edition), Butterworth-Heinemann, 2001 (Chapter 4)

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# Calculation of mean radiant temperature

- $T_{mrt}^4 = T_1^4 F_{P-1} + T_2^4 F_{P-2} + T_3^4 F_{P-3} + \ldots\ldots T_n^4 F_{P-n}$

| | |
|---|---|
| $T_{mrt}$ | mean radiant temperature, K |
| $T_n$ | Temperature of surface n, K |
| $F_{P-n}$ | Angle factor between a person and a surface n |

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# Operative temperature

- *ISO 7730:2005* – ‘uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment’

- *Nilsson, P.E. (ed.): Achieving the Desired Indoor Climate. Energy Efficiency Aspects of System Design, IMI Indoor Climate and Studentlitteratur 2003, ISBN 91-44-03235-8.* – ‘the uniform temperature of surrounding air and surfaces, which results in the same heat loss as the actual environment’

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# Calculation of operative temperature

- Operative temperature

$$t_{op} = \frac{h_c t_a + h_r \bar{t}_r}{h_c + h_r} \rightarrow T_{op} = a \cdot t_a + (1-a) \cdot \bar{t}_r$$

a=0.5

$$T_{op} = \frac{t_a + \bar{t}_r}{2}$$

| | |
|---|---|
| $t_a$ | air temperature |
| $\bar{t}_r$ | mean radiant temperature |
| $h_c$ | convective heat transfer coefficient |
| $h_r$ | mean radiation heat transfer coefficient |

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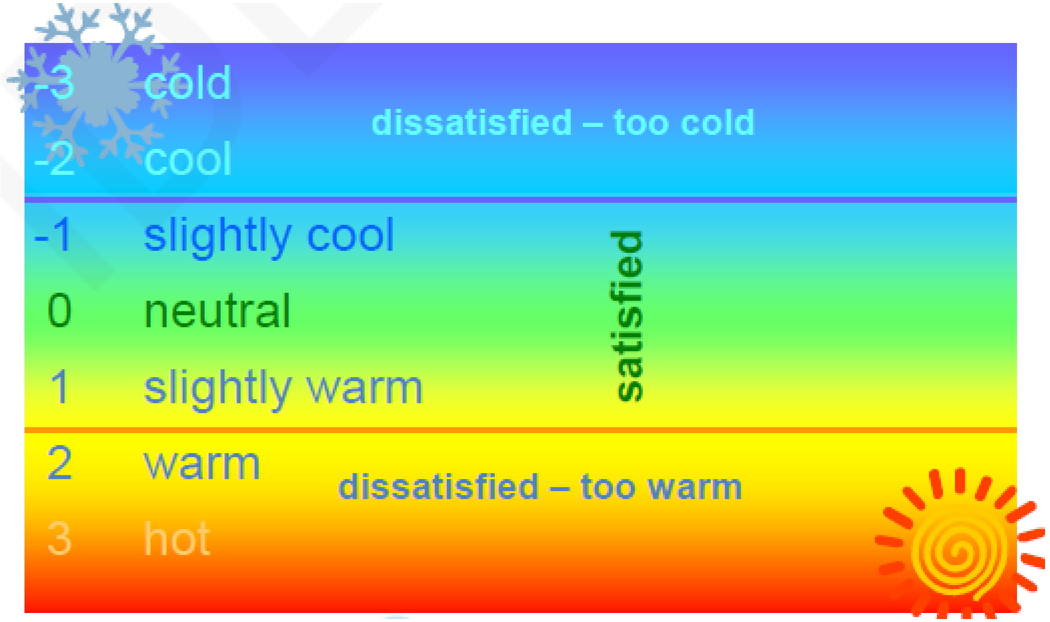
# Definition of PMV

- **PMV (Predicted Mean Vote)**:
  - Index using a scale (psychophysic 7-point scale) from +3 (Hot) to -3 (Cold), where 0 corresponds to thermal neutral
  - PMV-values can be calculated for a given situation on the basis of air temperature, mean radiant temperature, air velocity, humidity, activity and clothing level (see EN ISO 7730:2005)

***Seven-point thermal sensation scale***




Ref. IDES-EDU : http://www.ides-edu.eu/



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# Calculation of PMV - ISO 7730:2005

$$PMV = [0.303\exp(-0.036m) + 0.028] \bullet \begin{bmatrix} m - w - 0.00305(5733 - 6.99(m-w) - p) \\ -0.42(m - w - 58.15) - 0.000017m(5867 - p) \\ -0.0014m(307 - T_a) - F \end{bmatrix}$$

$$F = 3.96 \cdot 10^{-8} f (T_{cl}^4 - T_{mrt}^4) + f\, h (T_{cl} - T_a)$$

$$h = \max\{2.38(T_{cl} - T_a)^{1/4}; 12.06\sqrt{v}\}$$

$$T_{cl} = 308.9 - 0.028(m - w) - R\,F$$

m, metabolic rate, $W/m^2$
w, effective mechanical power, $W/m^2$
F, heat exchange due to radiation and convection, $W/m^2$
h, the convective heat transfer coefficient, $W/(K.\ m^2)$
p, the water vapour partial pressure (Pa)

$T_{cl}$, the clothing surface temperature (K)
f, the clothing surface area factor
v, the relative air velocity (m/s)
R, the clothing insulation, $(m^2.K/W)$
$T_a$, the air temperature (K)
$T_{mrt}$, the mean radiant temperature (K)



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# Definition of PPD

- Predicted Percentage of Dissatisfied (PPD) Can be derived from PMV and this relates to the temperature range.
- $PPD = 100 – 95 \cdot \exp(-0.03353 \cdot PMV^4 – 0.2179 \cdot PMV^2)$
- PPD is the predicted percent of dissatisfied people at each PMV. As PMV changes away from zero in either the positive or negative directions, PPD increases.


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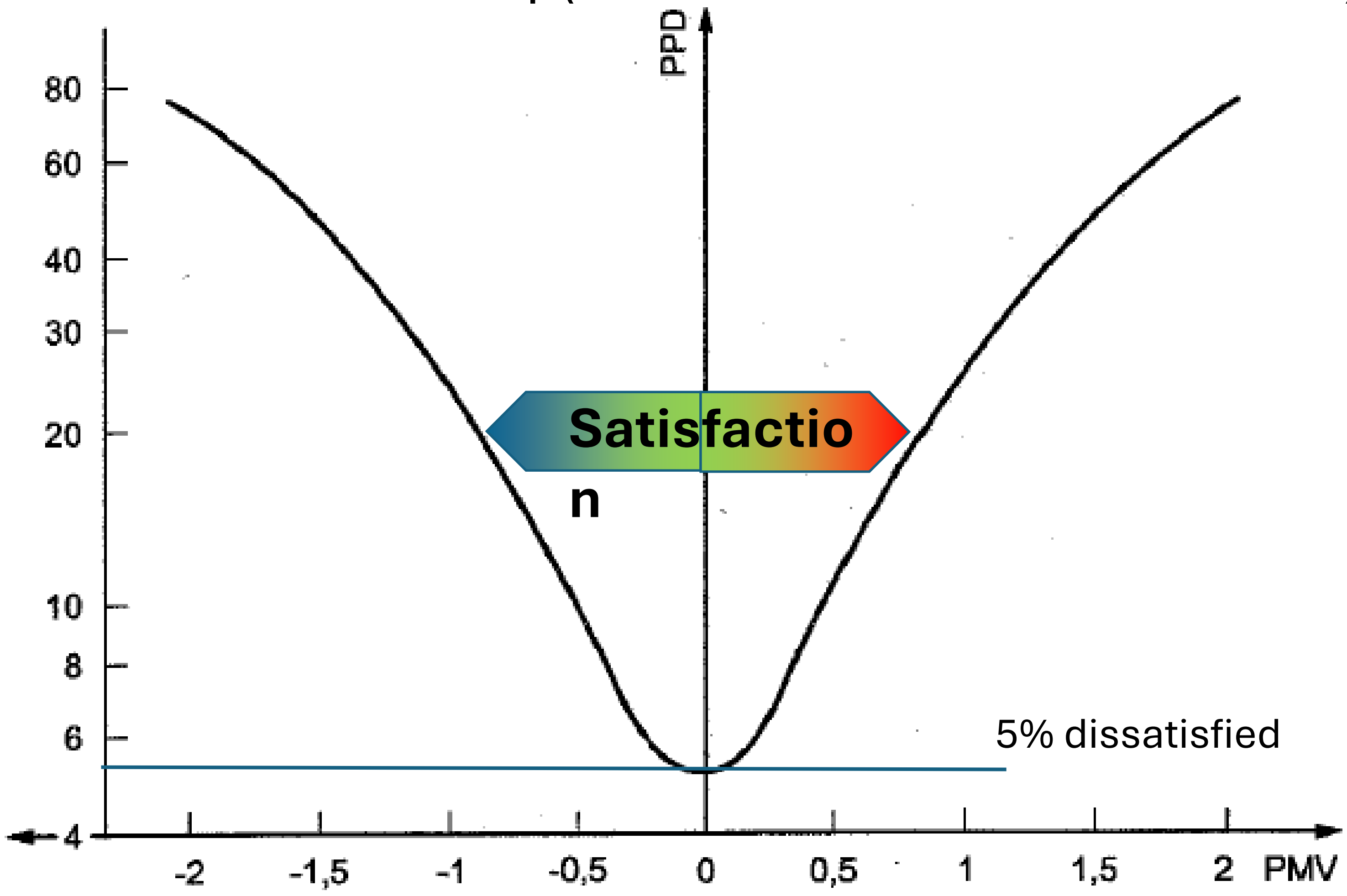
# PMV and PPD (ISO 7730:2005)

$$PPD = 100 - 95 \cdot \exp(-0.033\,53\,PMV^4 - 0.217\,9\,PMV^2)$$




PPD as a function of PMV



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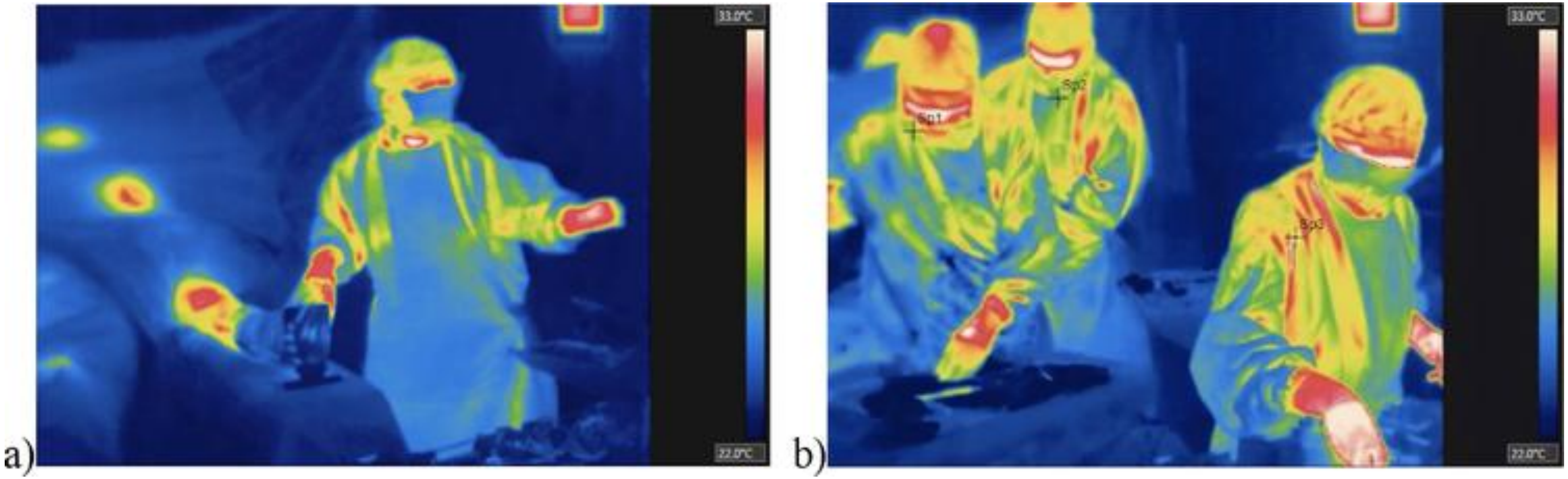
# Thermal comfort in ORs with LAF

What is thermal comfort level of patient and surgical teams after 2 h and how to improve it in ORs with laminar flow?



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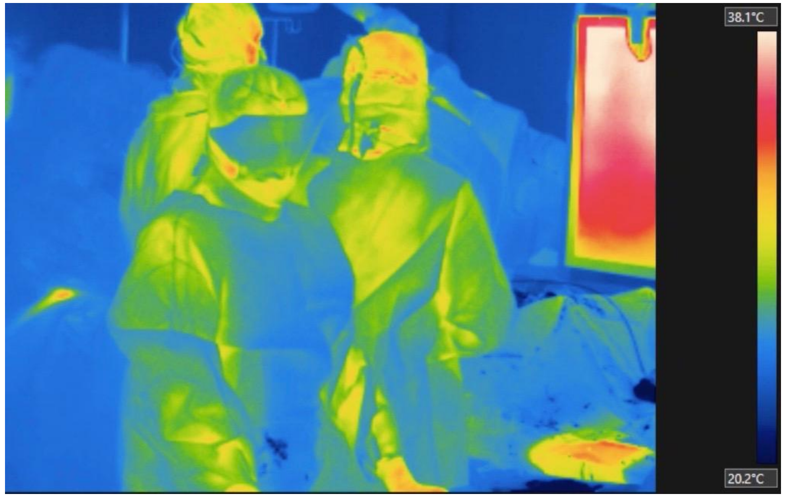
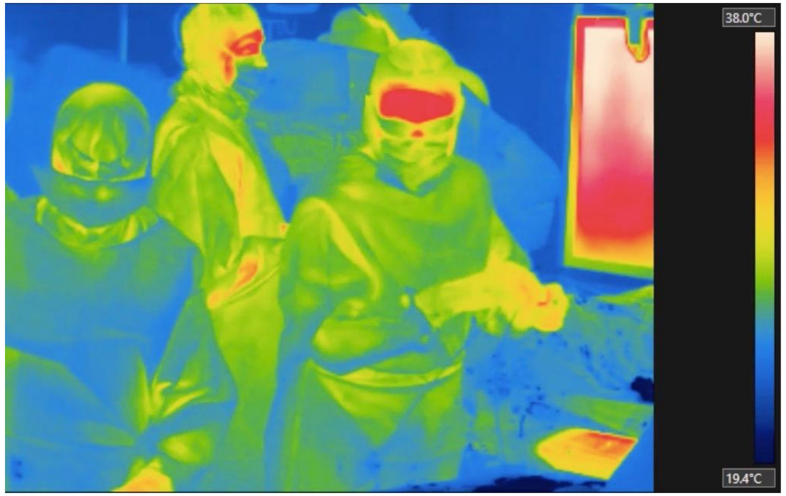
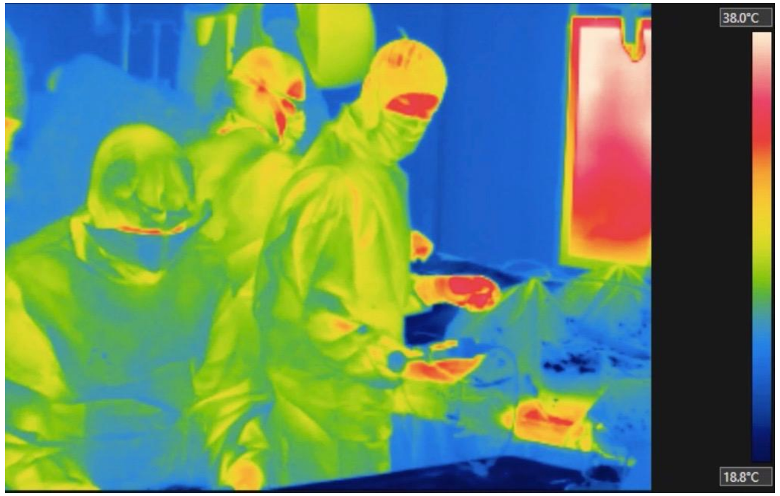
# Thermal comfort in ORs with MV




40 minutes surgery




1 hour, 40 minutes surgery




2 hours, 35 minutes surgery

- The thermal camera shows the temperature distribution of the surface temperatures of the surgeon, assistant surgeon and sterile nurse during a surgery
- Dark blue is equivalent to approximately 20 °C, while the white colour is equivalent to 38 °C.

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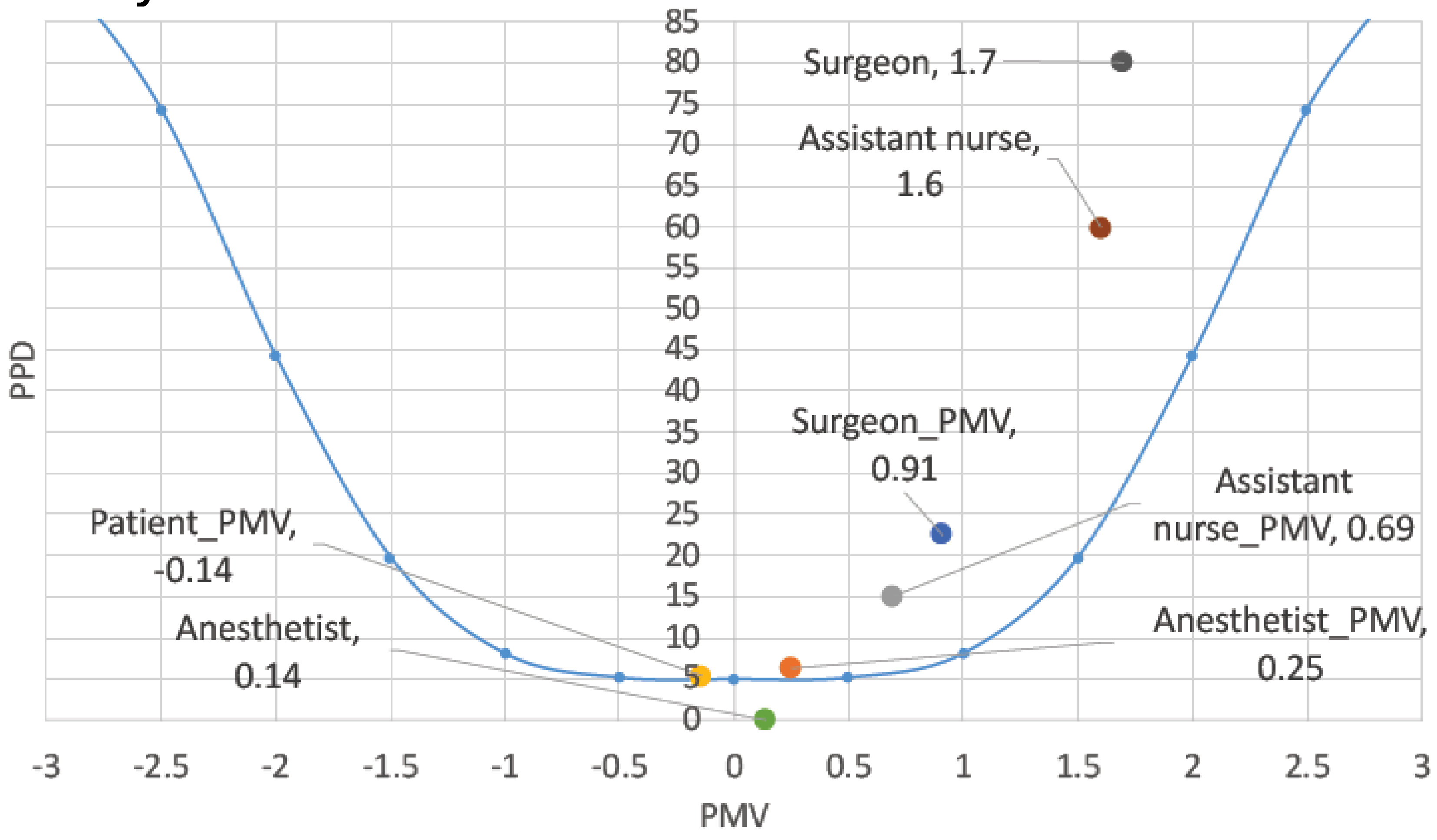
# Predicted VS. real thermal comfort in ORs

- Predicted VS. real thermal comfort in operating rooms with mixing ventilation systems

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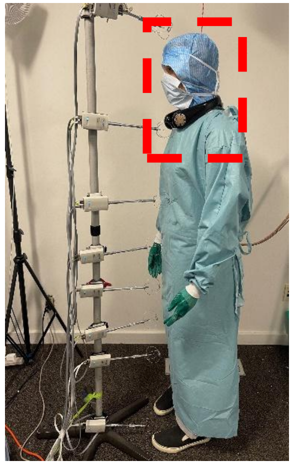
# New solutions to improve OR thermal comfort

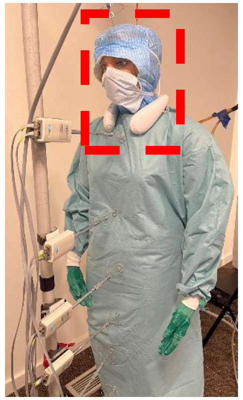
Solution 1: External nozzle air jet



Solution 2: Neck air conditioner

Solution 3: Through back fan

Solution 4: Mixing wall fan



Solution 5: Neck fan

Solution 6: Within the gown wearable

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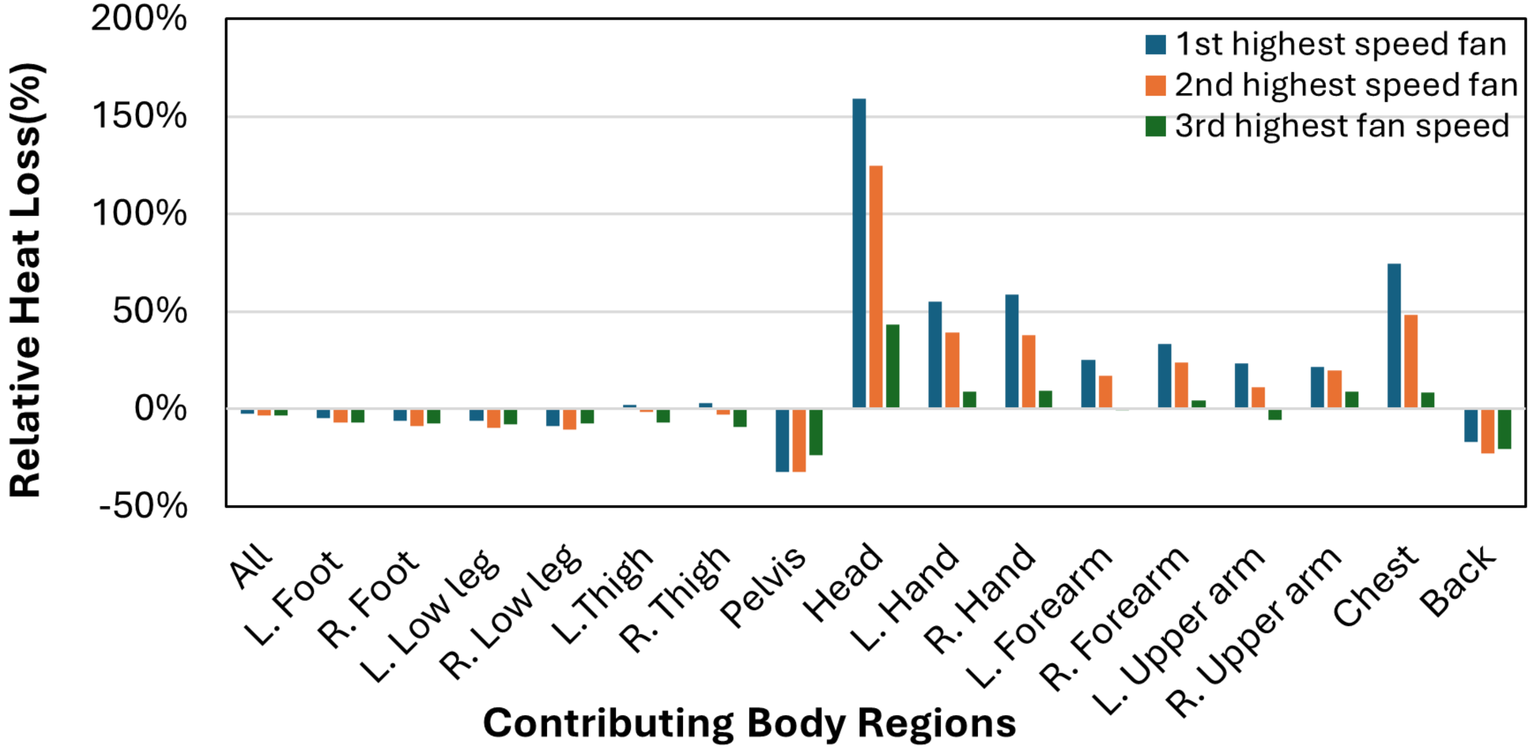
# Solution 1: External nozzle air jet

**Relative heat losses were increased approximately:**

- 160% for the head
- 75% for the chest




**Relative heat loss of different body parts**

**Solution 1: External nozzle air jet**

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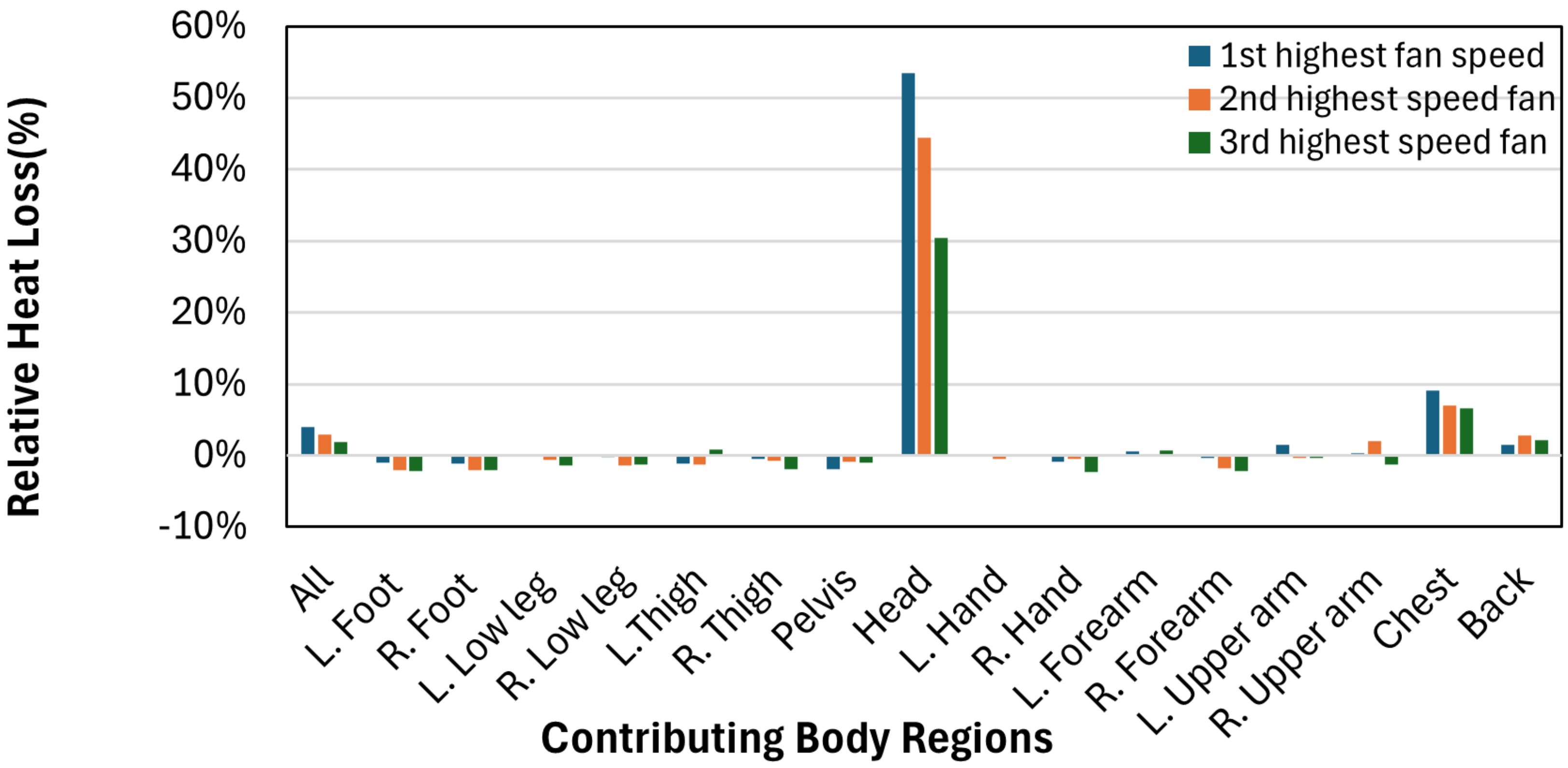
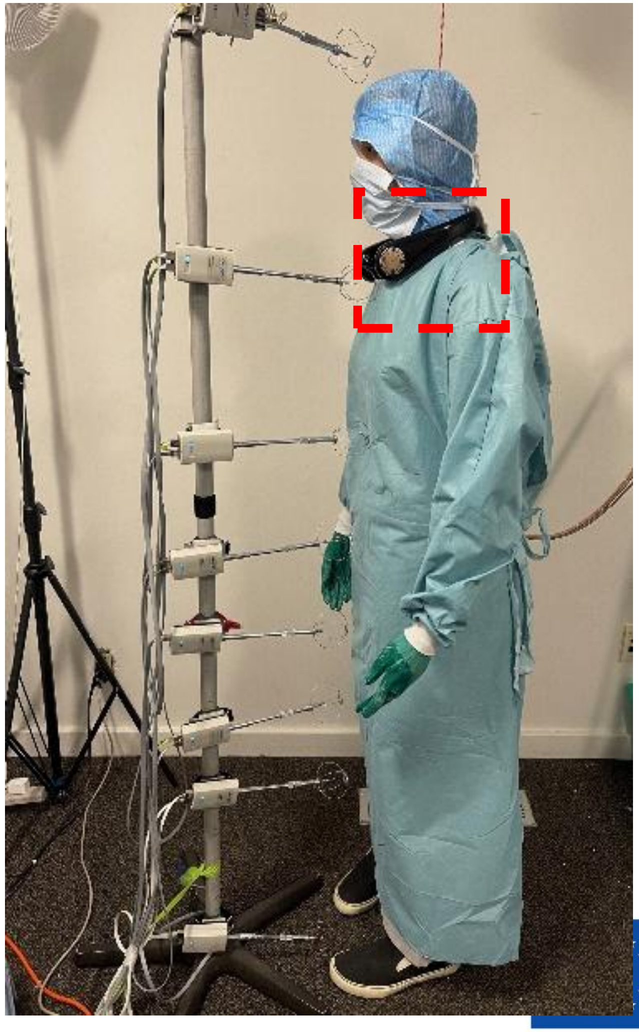
# Solution 2: Neck air conditioner

**Relative heat losses were increased approximately:**

- 50% for the head
- 3% for the chest




**Relative heat loss of different body parts**



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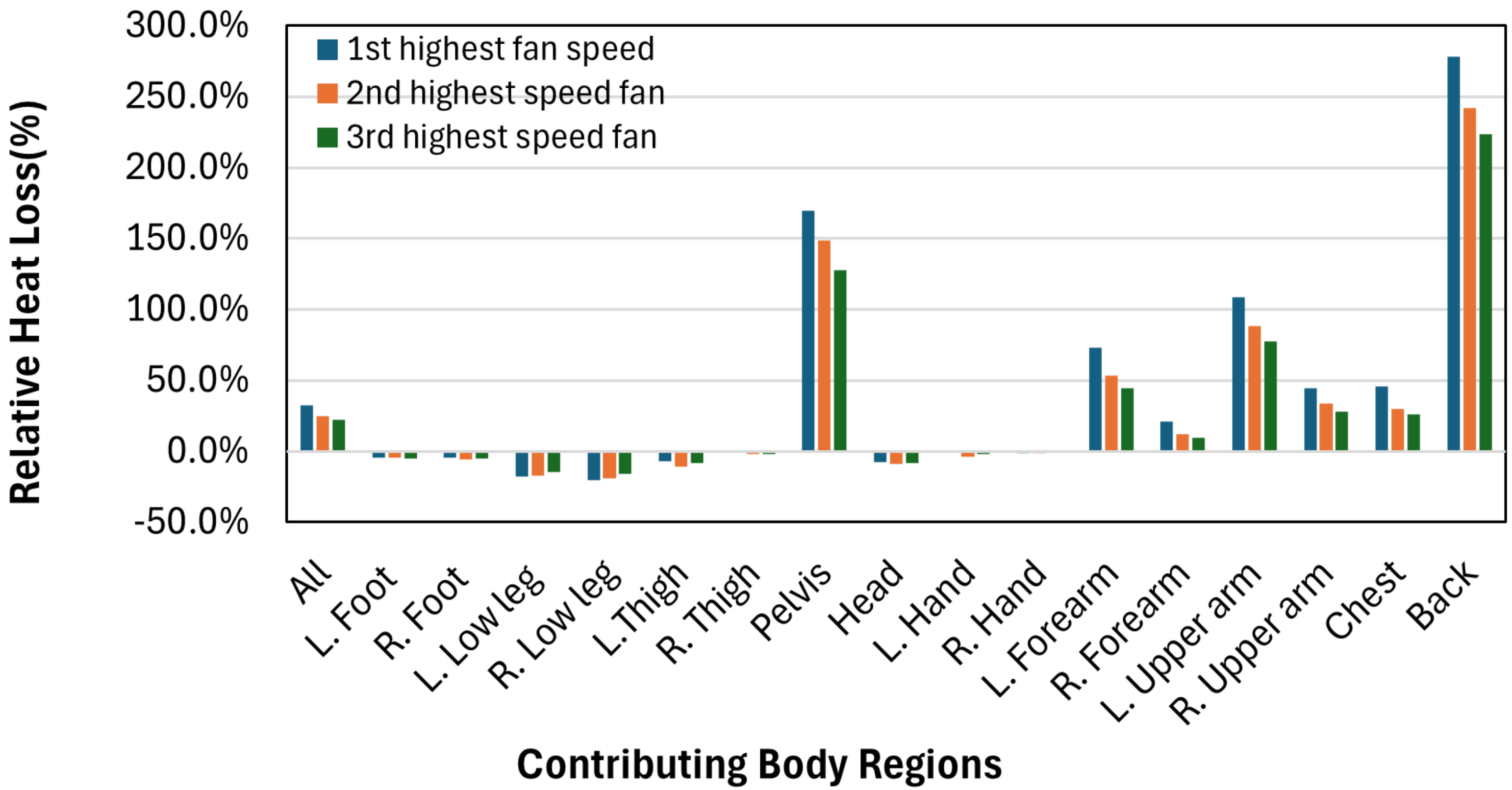
# Solution 3: Through the gown wearable fan

**Relative heat losses were increased approximately:**

- 160% for the Pelvis
- 280% for the back




**Relative heat loss of different body parts**

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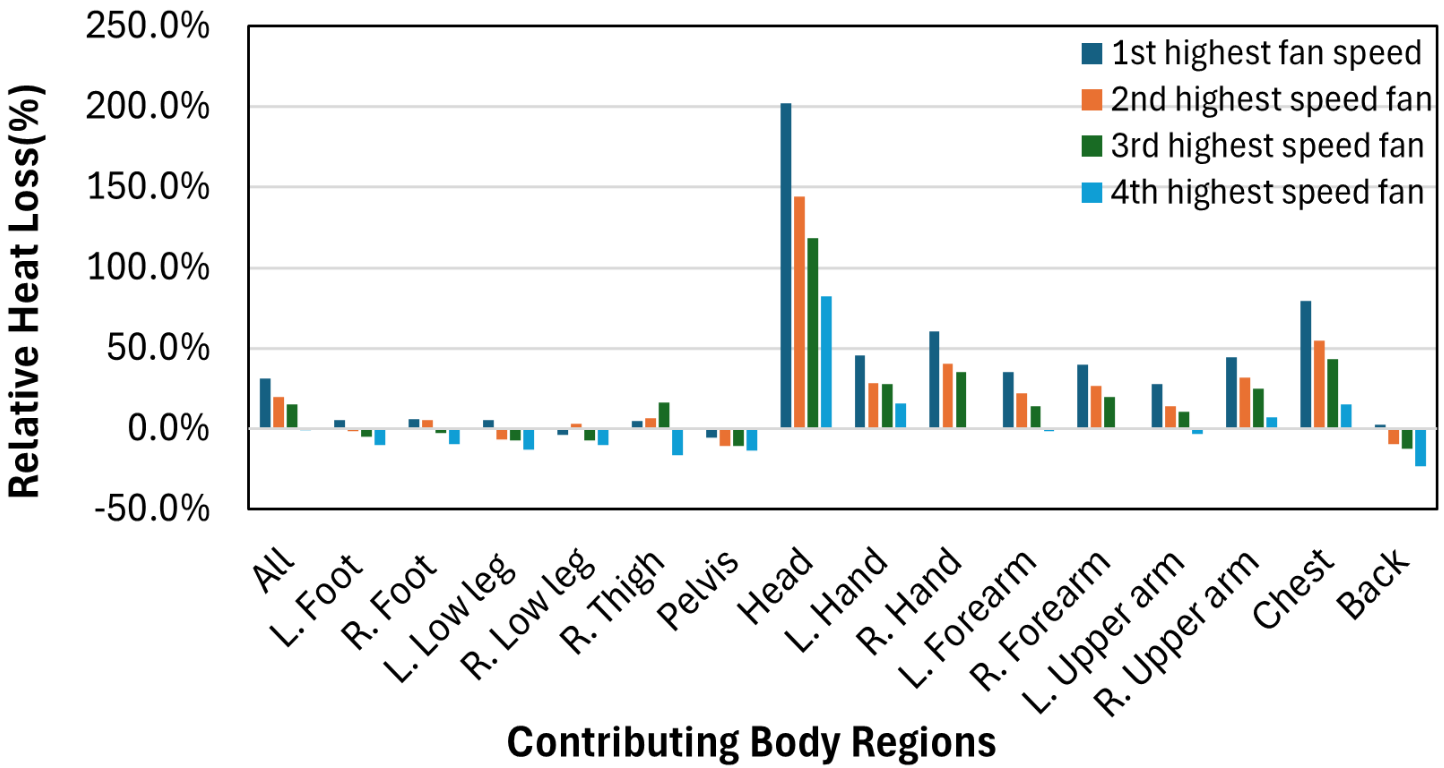
# Solution 4: Wall-mounted cooling fan

**Relative heat losses were increased approximately:**

- 200% for the head
- 75% for the chest




**Relative heat loss of different body parts**

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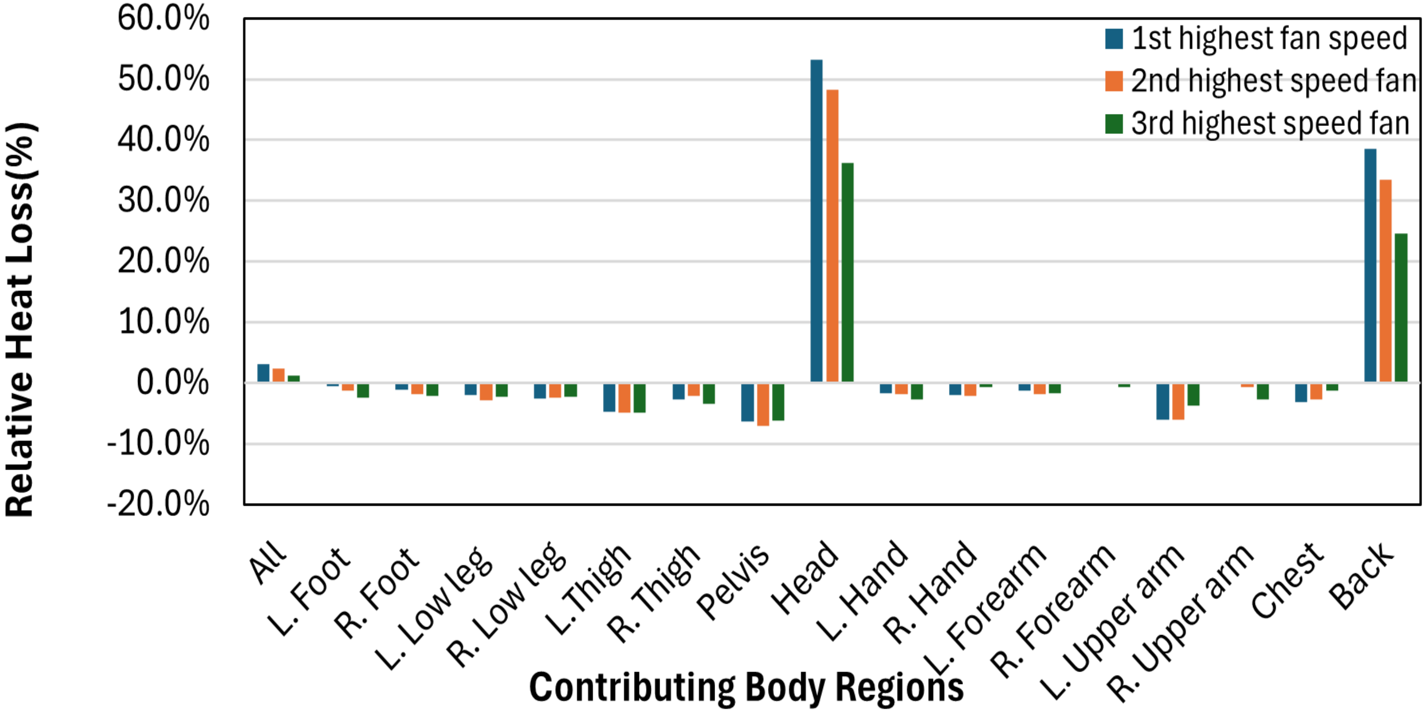
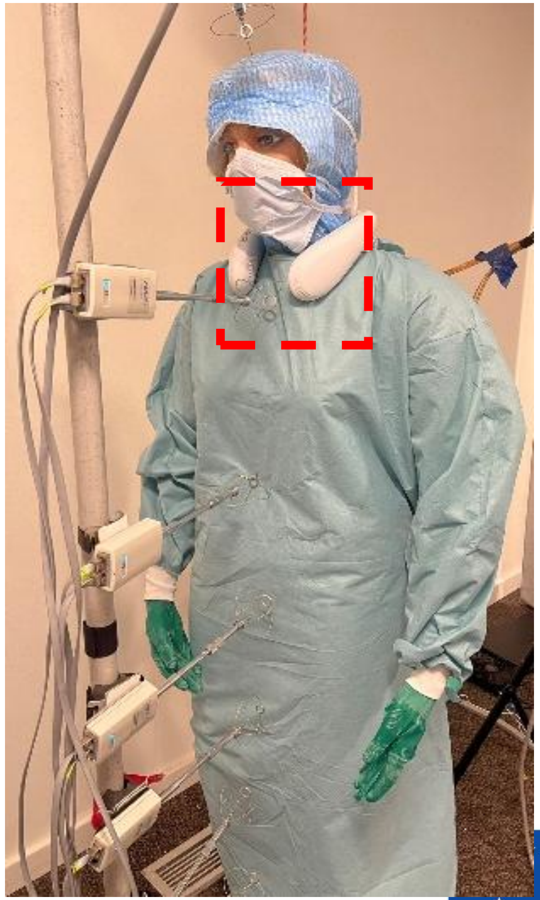
# Solution 5: Neck fan with additional air jet

**Relative heat losses were increased approximately:**

- 55% for the head
- 40% for the back




**Relative heat loss of different body parts**



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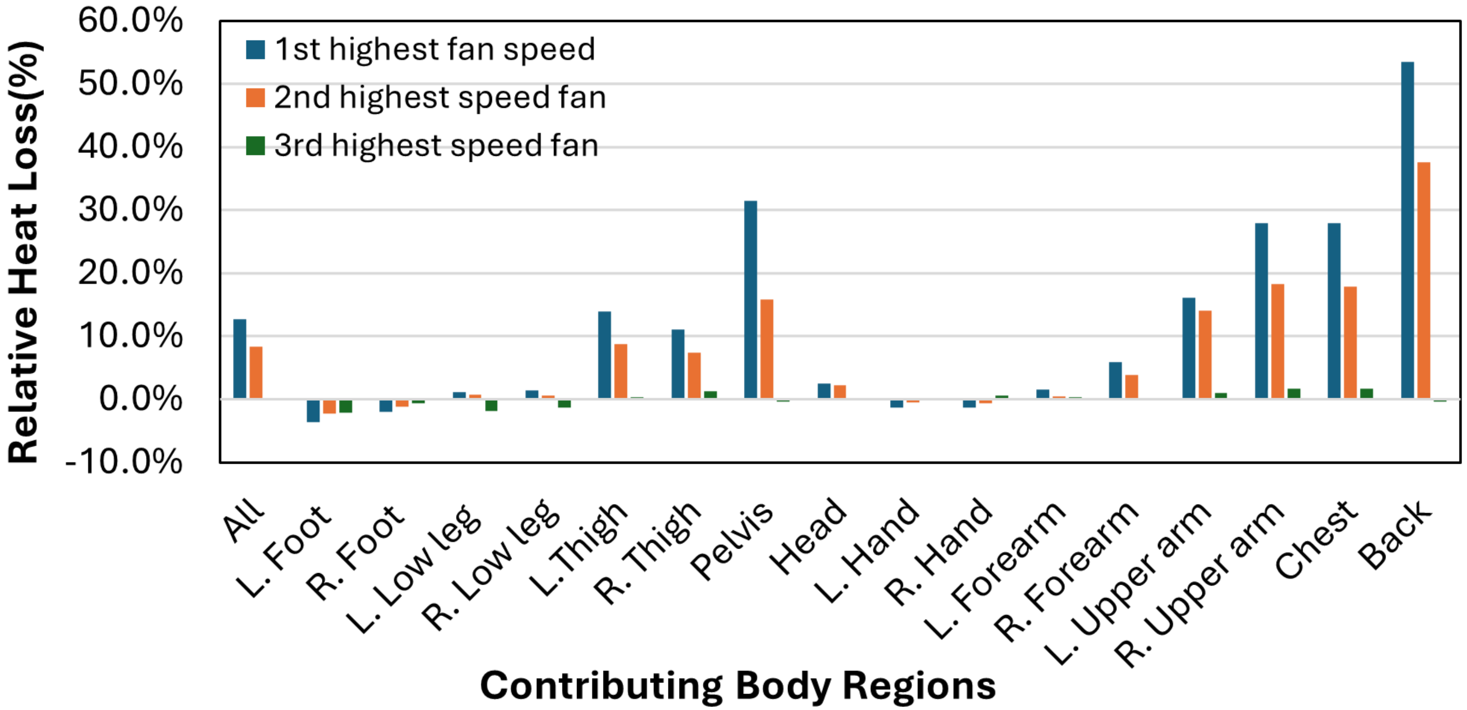
# Solution 6: within the gown wearable

**Relative heat losses were increased approximately:**

- 55% on the back
- 30% for pelvis




**Relative heat loss of different body parts**

**Solution 6: Within the gown wearable**

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# Discussions

**What are thermal comfort level of occupants in your project?**

**How to measure / improve thermal comfort in your project?**

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