Ventilation, indoor environment and energy consumption in health care facilities

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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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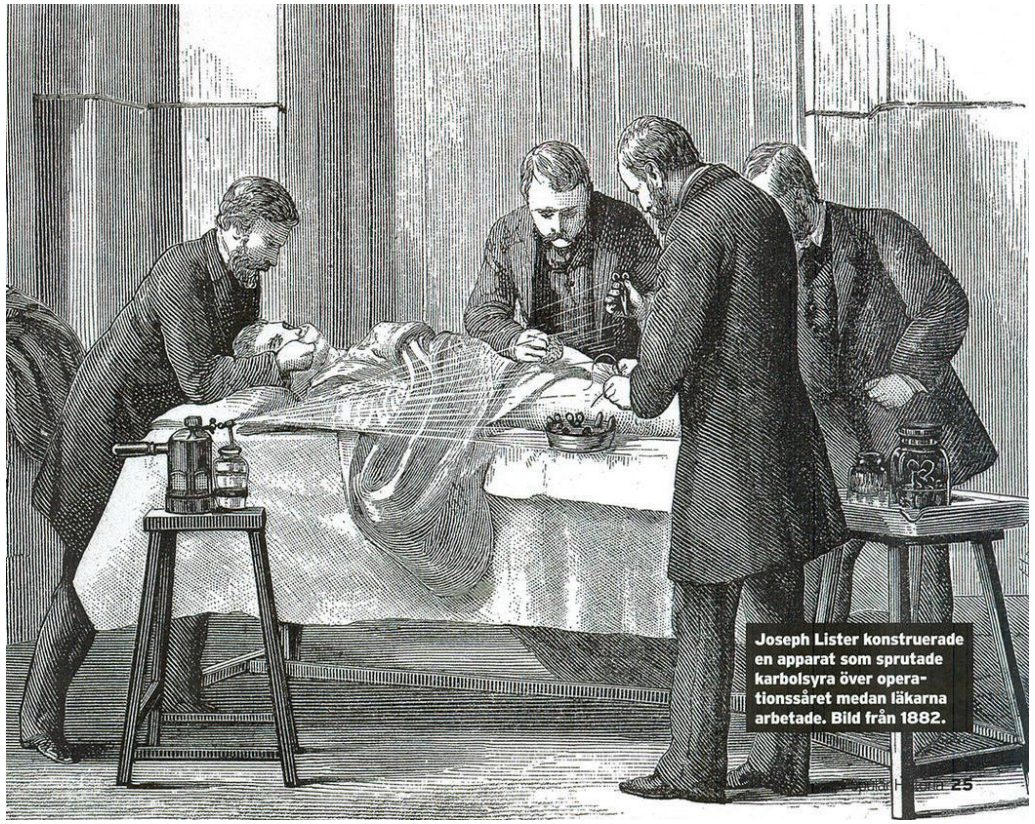
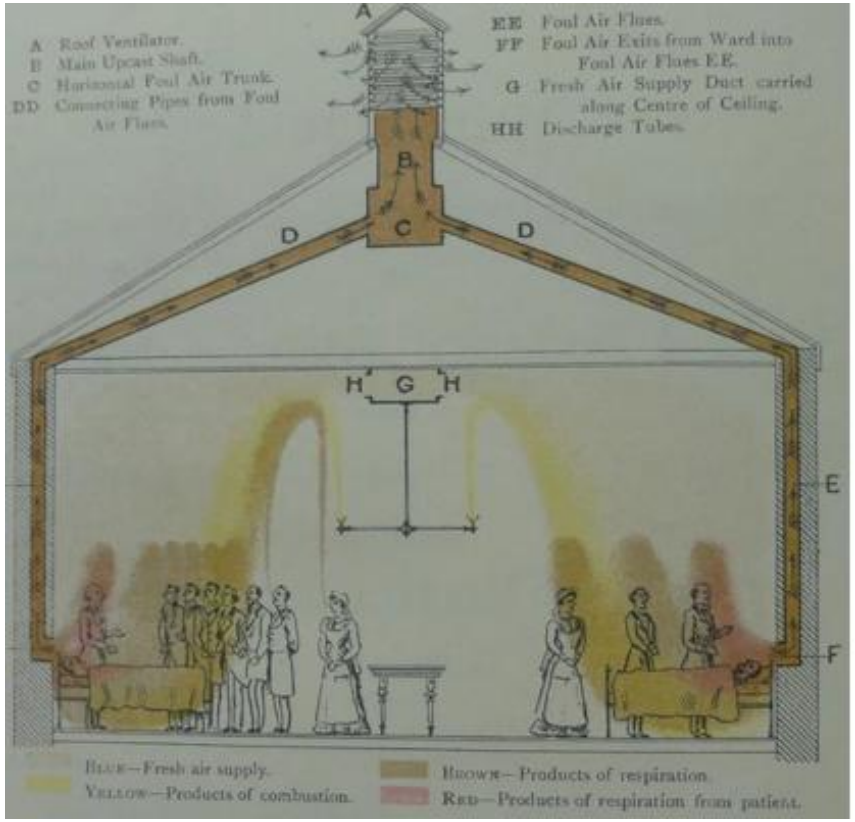
100 years ago…

1882 Joseph Lister – Phenol (fenol, karbolsyre)



Joseph Lister konstruerade en apparat som sprutade karbolsyra över operationssåret medan läkarna arbetade. Bild från 1882.

1899 Robert Boyle & Son



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An operating room with laminar airflow system

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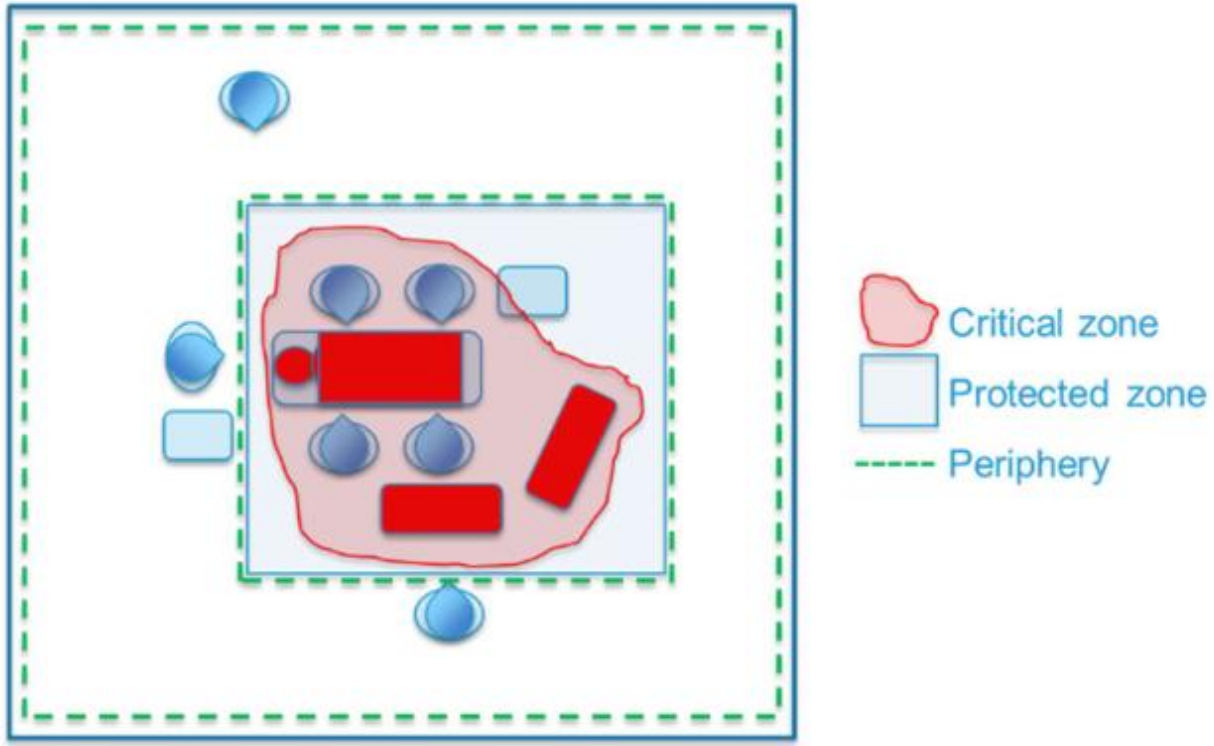
EU TC156/W18 - R3 Nordic Guideline for Hospital Ventilation - General Requirements, Operating Suites, and Isolation Rooms (20.9.2023)

OR with Protected Zone principle



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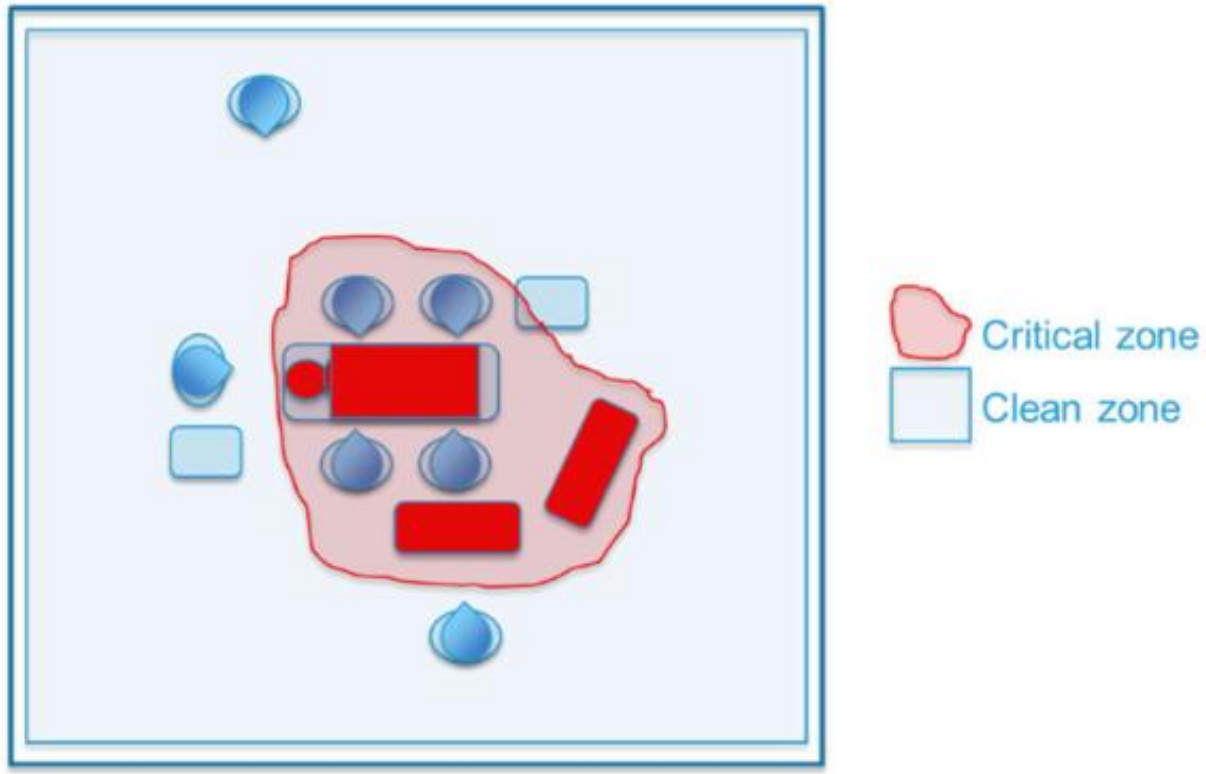
EU TC156/W18 - R3 Nordic Guideline for Hospital Ventilation - General Requirements, Operating Suites, and Isolation Rooms (20.9.3023)

OR with Dilution mixing principle



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R3 Nordic Guideline for Hospital Ventilation - General Requirements, Operating Suites, and Isolation Rooms (20.9.3023)

Table 1. Ventilation classes

Ventilation Class	Flow direction	Sound level of the ventilation system** dB(A)	Room type
CL1	Outward flow from clean to less clean	≤45	Operating rooms, additional terminal filtration of ISO 35H or better is required*
CL2		≤45	
CL3		≤40	Other rooms in OR department
CL4	N.A.	≤ 40	Treatment/consultation room, staff meeting room etc.
CL5	N.A.	≤30**)	Patient ward
CL6	Outward or inward flow**)	≤30	Isolation Room ***)

* Detailed performance specifications in Part 2.
** With minimum airflow rate, when patient only is present.
*** Detailed performance specifications in Part 3.

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R3 Nordic Guideline for Hospital Ventilation - General Requirements, Operating Suites, and Isolation Rooms (20.9.3023)

Table 2. Requirements for indoor environment for general room types

Room Type	Ventilation class	Amount of outdoor air (ODA)*	Relative Humidity***	Temperature
			%	°C
Patient room with occupancy of permanent nature **	CL5	0,010 m^3/s,patient and 0,001 $m^3/s,m^2$ ****	Air humidification is not required	Heating season: **20-24** Cooling season: **23-26**
Rooms for Staff, and other general areas**	CL4	0,007 m^3/s,person and 0,000,7 $m^3/s,m^2$ *****	Air humidification is not required	Heating season: **20-22** Cooling season: **23-26**

* Additional ventilation may be required by local regulations or for microbiological and chemical dilution and heat gains and losses etc.
** Visitors and staff should be taken into account separately based on variable usages. There may be elevated airborne exposure risk in close contact with the patient, Kalliomäki et al (2020)
***Condensation of moisture on components or surfaces is not allowed. If humidification is needed for specific purpose, it should be defined in URS.
**** Category I and low polluting building according to EN16798-1
***** Category II and Low polluting building according to EN16798-1
Note 1: Bold indicates the range over which the parameter may float.

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Performance criteria occupancy state - at rest

Table 3. **Protected Zone system: At Rest** Performance criteria for OR*) room **Ultra clean air**

			At rest	
	Standard	Specification	Protected zone	Periphery area
Particle concentration	ISO 14644-1	≥0.5µm	ISO 5	ISO 6
Segregation test	ISO 14644-3	By National test method	Yes **)	n.a.
Recovery test	ISO 14644-3	100:1	n.a.	<10min
OR-lamp wake Recovery test	ISO 14644-3	100:1	<5min**)	n.a.
Not only ventilation based aspects				
Microbiological test Air	ISO 14698	Cfu/m^3	<1	<1

*) also applicable for the Instrument Lay-up area

**) when implemented by national test method (SIS-TS-39-2012/DIN 1946-4/HTM-03-01/Önorm H6020/VCCN RL-7)

European Standardization for Ventilation in Hospitals Operating Rooms - CEN TC 156 WG18

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R3 Nordic Guideline for Hospital Ventilation - General Requirements, Operating Suites, and Isolation Rooms (20.9.3023)

Table 3. Thermal, ventilation and air quality requirements for operating suite

Room Type	Ventilation Class (See Table 2)	Amount of outdoor air (ODA)	Relative Humidity	Temperature
			%	°C
Operating room	CL1, CL2	≥0,275 m^3/s *) **)	**<60** (at 21 °C) Air humidification is not required	**18-26**
Instrument lay-up room	As associated operating room	0,007m^3/s,person and 0,0007 $m^3/s,m^2$	**<60** (at 21 °C) Air humidification is not required	
Other rooms	CL3			

*Additional ventilation may be required by local regulations or for microbiological and chemical dilution and heat gains and losses etc. The maximum number of people in the OR should be decided by the client.

** Minimum total value per room

Note 1: The presented minimum ventilation airflow rate is based on a situation where operating rooms are equipped with local exhaust systems for anesthetic gases and surgical smoke. If this is not the case, it is recommended to use higher airflow rate.

Note 2: Bold indicates the range over which the parameter may float.

Note 3: Patient temperature control is taken care of by medical thermal devices.

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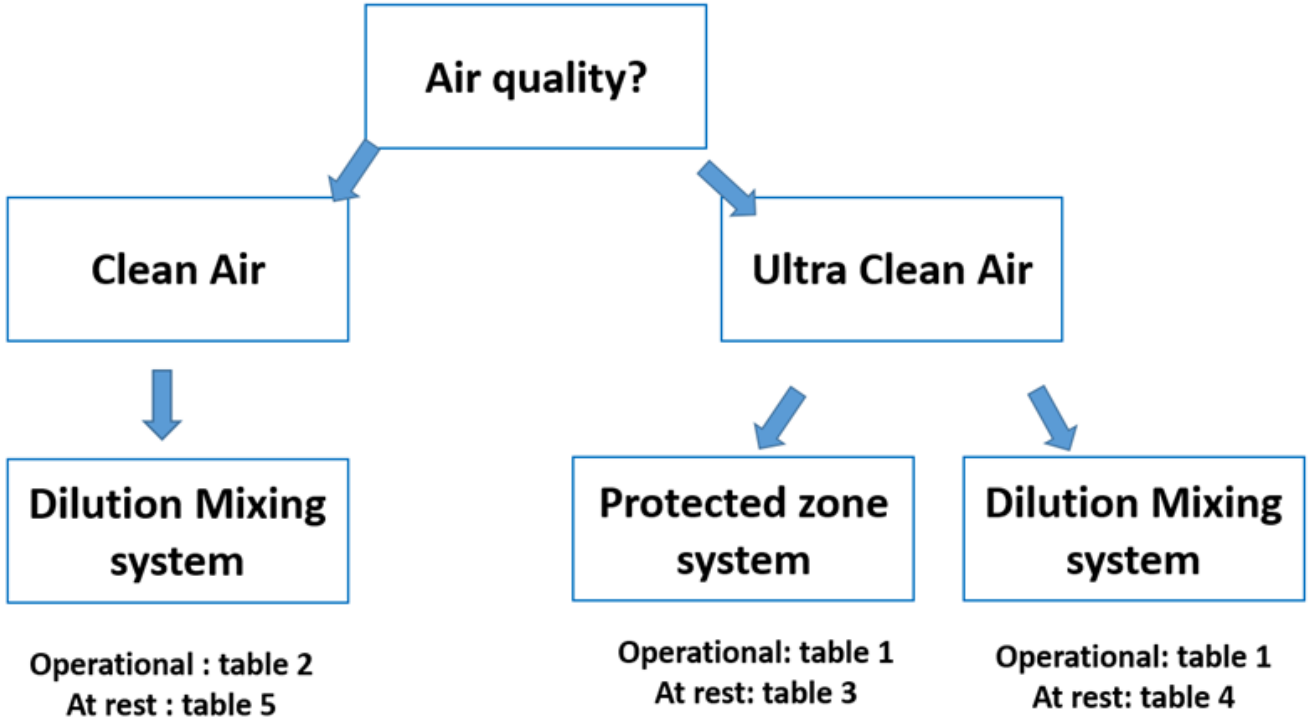
Performance Criteria

Performance criteria applicable to operating rooms and lay-up rooms are defined for the specific area of interest when applicable, otherwise the criteria apply to the complete room. There are two main airflow concepts: Protected zone system and Dilution mixing system. With both system you can achieve Ultra clean air cleanliness levels.



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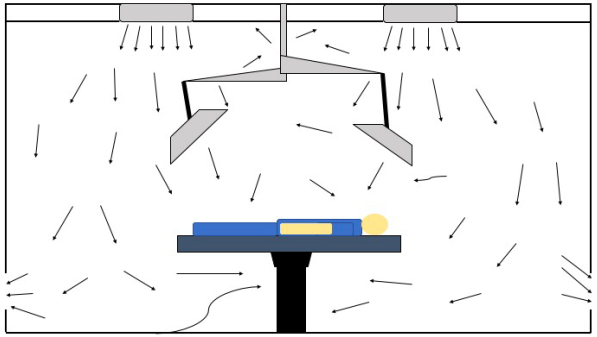
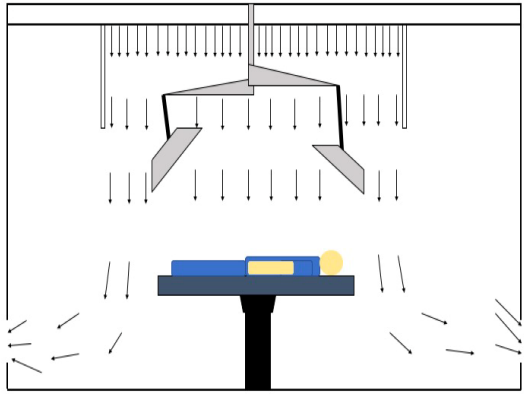
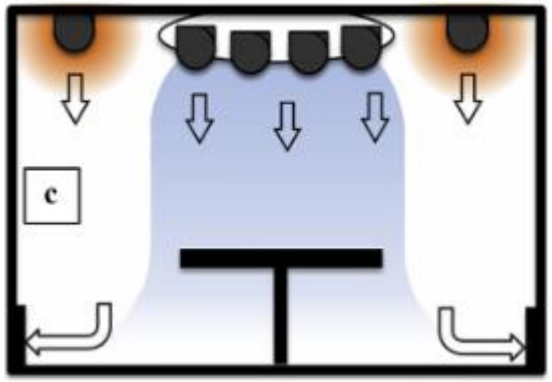
Ventilation solutions for operating rooms



Mixing ventilation



Laminar airflow ventilation



Temperature-Controlled Airflow (TAF)

Hybrid impinging airflow

- Allander ventilating system for clean rooms, US patent 3380369, Filed Feb 15, 1966

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Requirements for a laminar airflow (LAF)-equipped OR environment

Country	Supply Velocity (m/s)	Pressure difference (Pa)	Humidity (%)	Temperature (°C)	LAF diffuser size (m^2)	Maximum CFU/m^3
Austria	0.22-0.45	-	35-45	20-24	≥ 8 m^2	-
France	0.25-0.35	15 ± 5	-	19-26	-	10
Germany	≥ 0,23	-	30-50	19-26	≥ 3.2 × 3.2 m^2	4-10*
Netherlands	-	-	-	18-22	-	-
Norway	0.25-0.28	5-10	-	-	-	-
Switzerland	0.23-0.25	-	30	19-26	≥ 9 m^2	10
UK	0.38 m/s	25	35-60	18-25	≥ 2.8 × 2.8 m^2	10
USA	- *	4	20-60	20-24	≥ 3.0 × 3.0 m^2	-

(Aganovic A. 2019. PhD thesis)

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Requirements for a turbulent mixing ventilation (TMV)-equipped OR environment

Country	Standards	Temperature (°C)	Relative humidity (%)	The pressure difference between the operating room and adjacent rooms (Pa)	Minimum air change rate (ACH)	Applicable OR types
Brazil[108]	NBR 7256	20-24	<60	5	25 /15	Class1/Class2
China[109]	GB 50333	21–25	30–60	5–20	12/18/24	Class IV/III/II,
France[110]	NF S 90-351	19–26	45-65	10–25	25–30/15-20	Class 3/Class2
Germany[111]	DIN 1946/4	19–24	30–50	–	30-60	Class Ib
Japan[112]	HEAS-02-2004	22-26	50-55	–	>15	–
Norway [113]		–	–	5–10	20 ACH	–
Russian[114]	GOST R 52539-2006	18-24	>30	–	12-20	–
Spain [115]	UNE100713	22–26	45–55	5–20	20 ACH	Type A/B
Sweden[116]	SIS-TR 39	18-26	20-65	–	>20	
The U.K. [117]	HTM 03-01	18–25	35–60	20	25 ACH	General/UCV
The U.S.[118]	ASHRAE 170	20–24	20–60	4	20 ACH	Class B/C

- Y. Bi, 2024, PhD thesis

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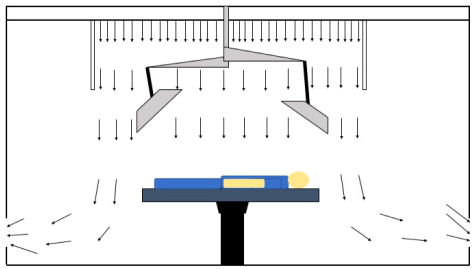
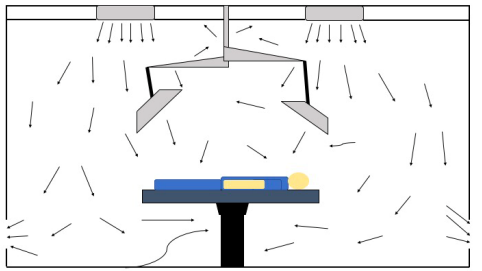
Main challenges today in operating rooms

- **Do surgical facilities affect laminar airflow?**
- **Whether mixing ventilation is better than laminar airflow?**
- **Can we get 10 CFU/m^3 level in ORs with mixing ventilation?**
- **How human activities affect CFU level in the OR environment?**
- **Exposure risk with combined airflow distribution in ORs**
- **How to improve thermal comfort level of patient and surgical teams?**
- **What's the energy consumption level in hospitals?**





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OR lab at NTNU

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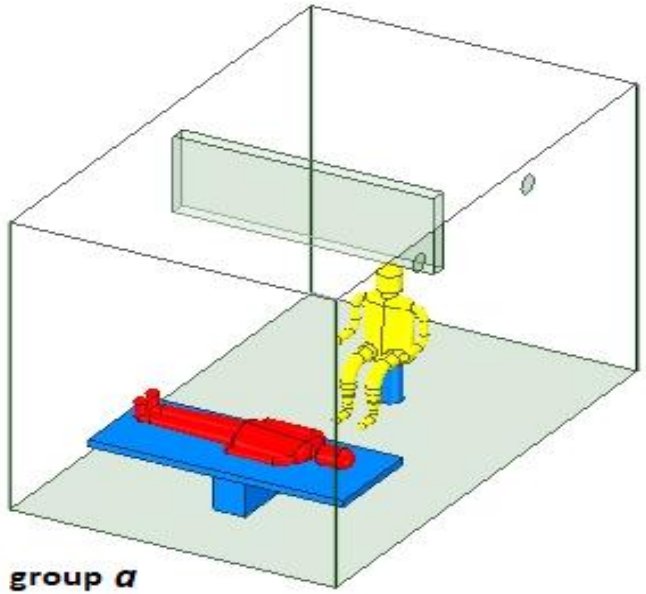
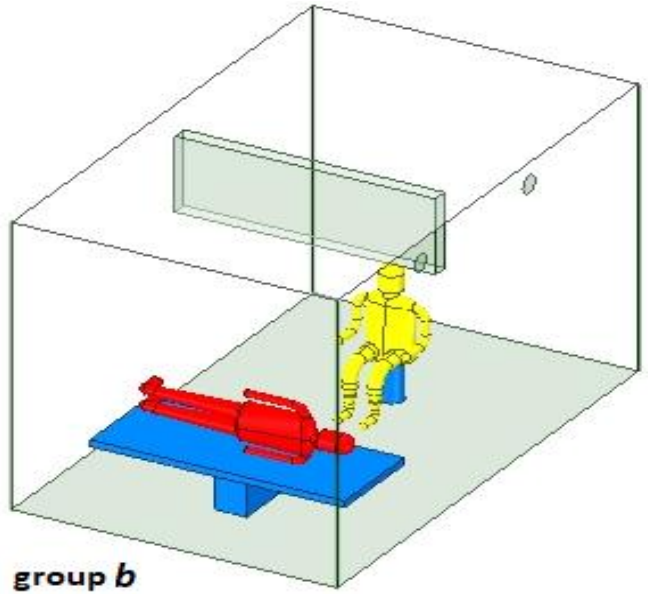
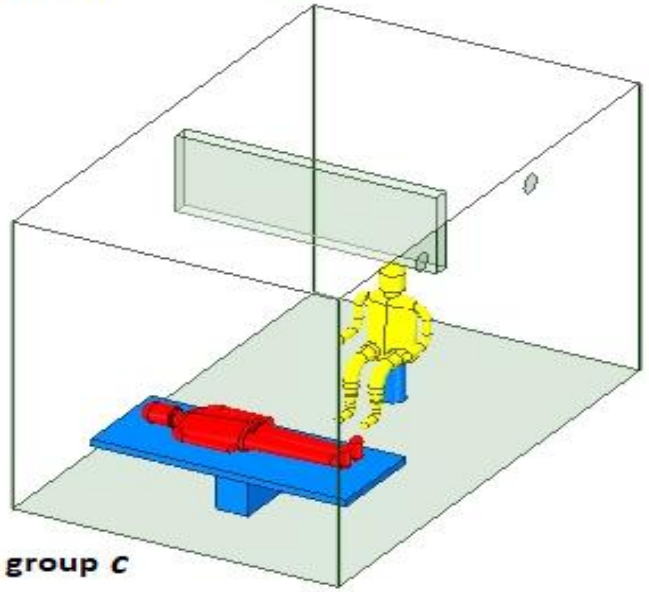
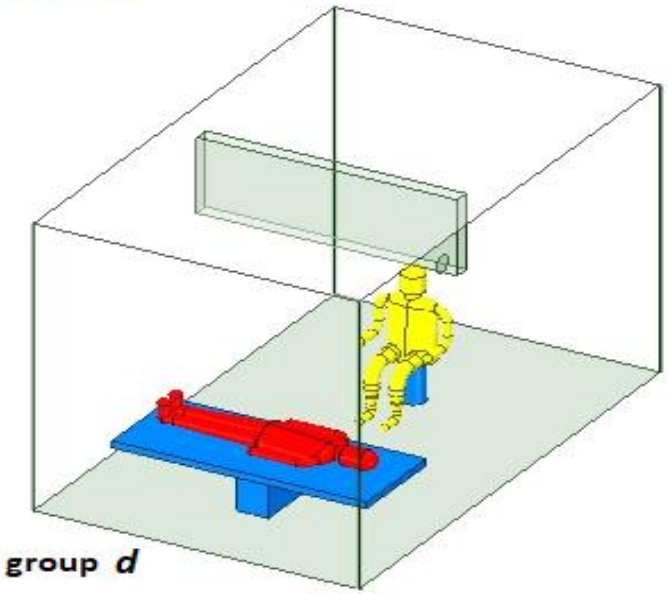
Exposure risk in an isolation room (5e)









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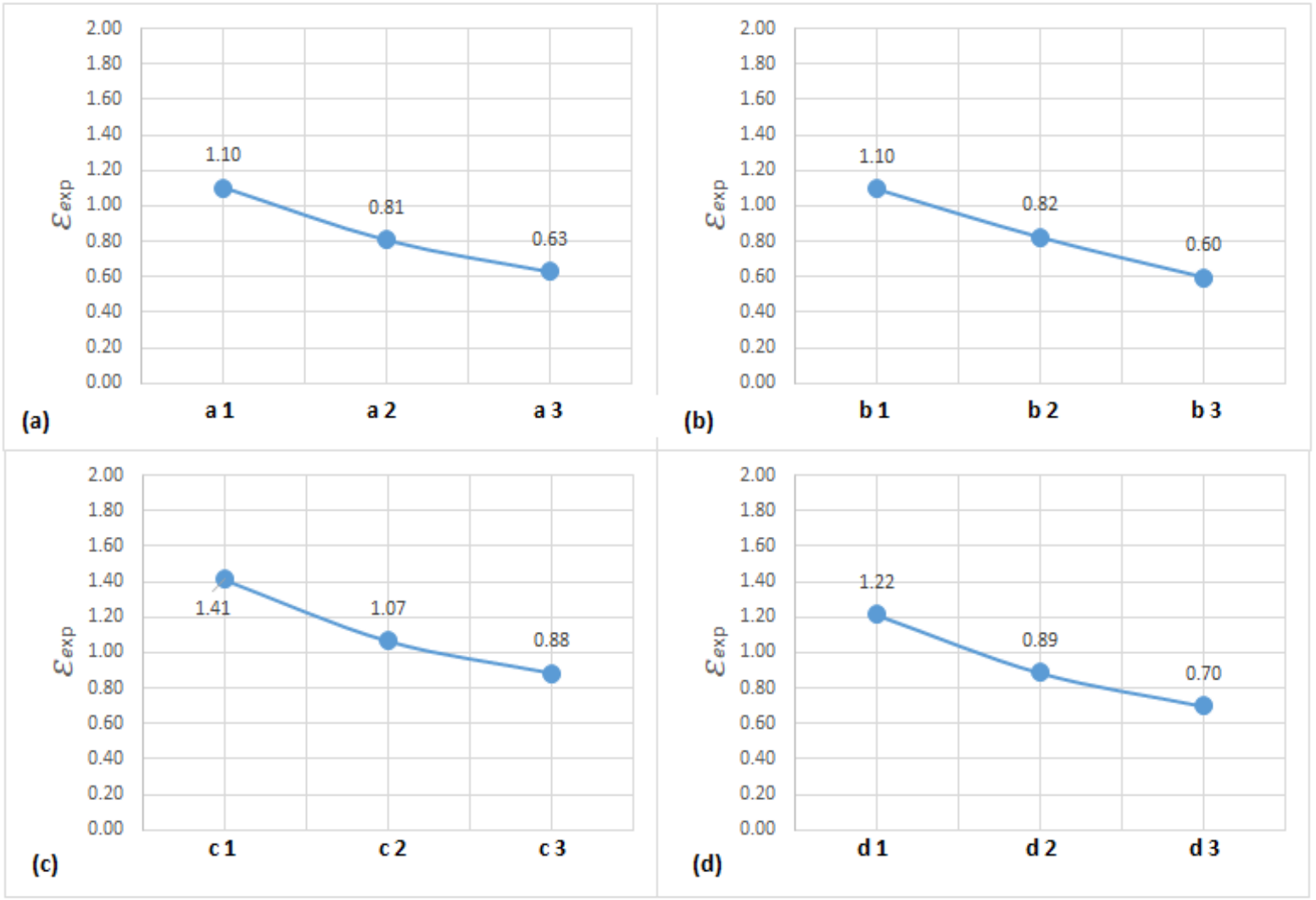
Exposure risk in an isolation room (5e)



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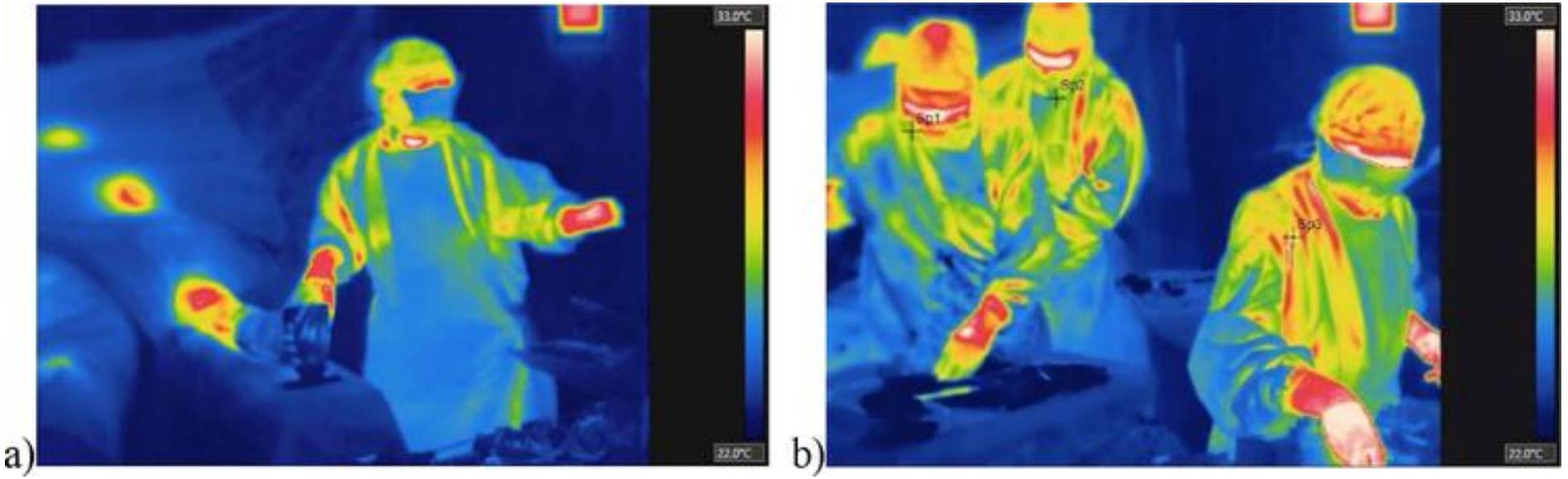
What is thermal comfort level of patient and surgical teams after 2 h and how to improve it in laminar flow?



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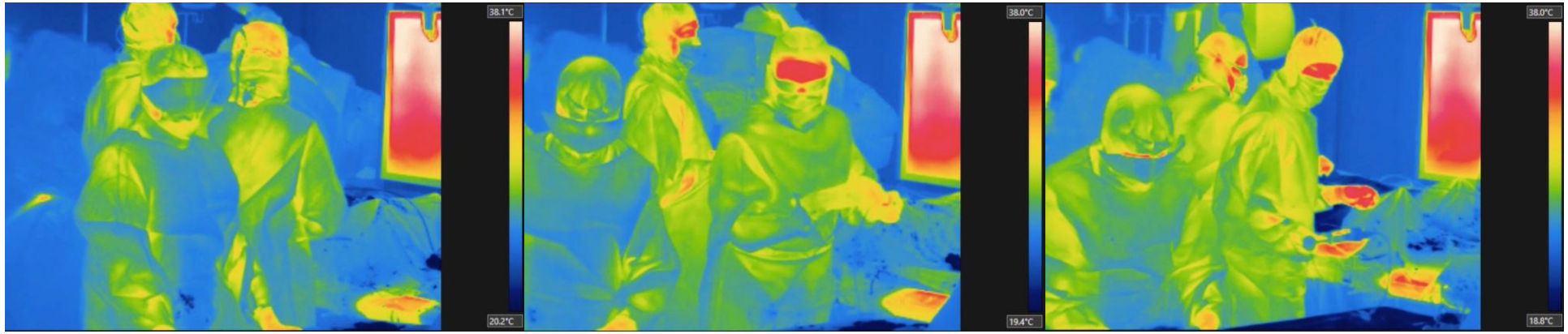
Thermal images – in the operating room with Mixing Ventilation



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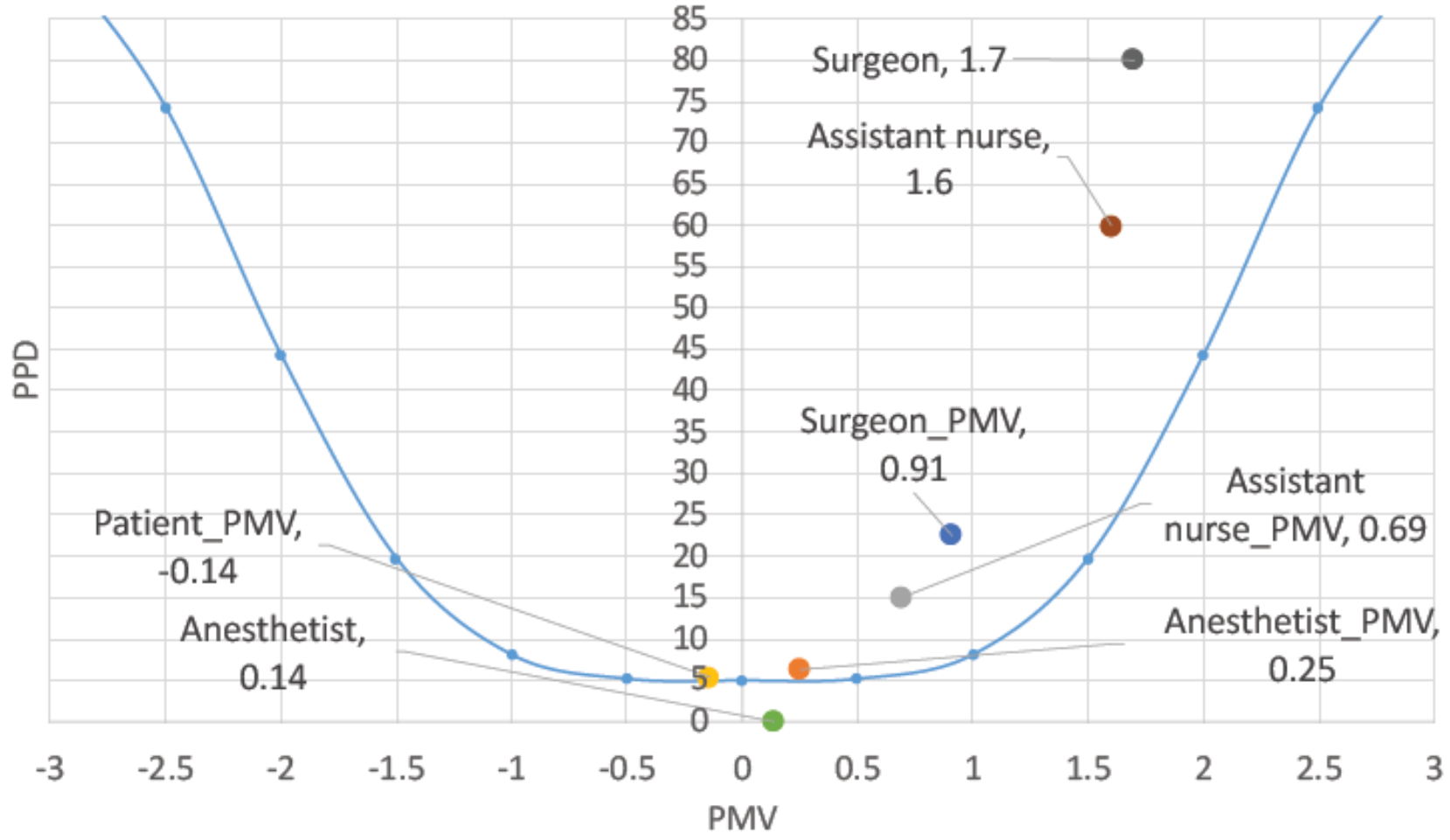
Predicted VS. real thermal comfort in operating rooms with mixing ventilation systems



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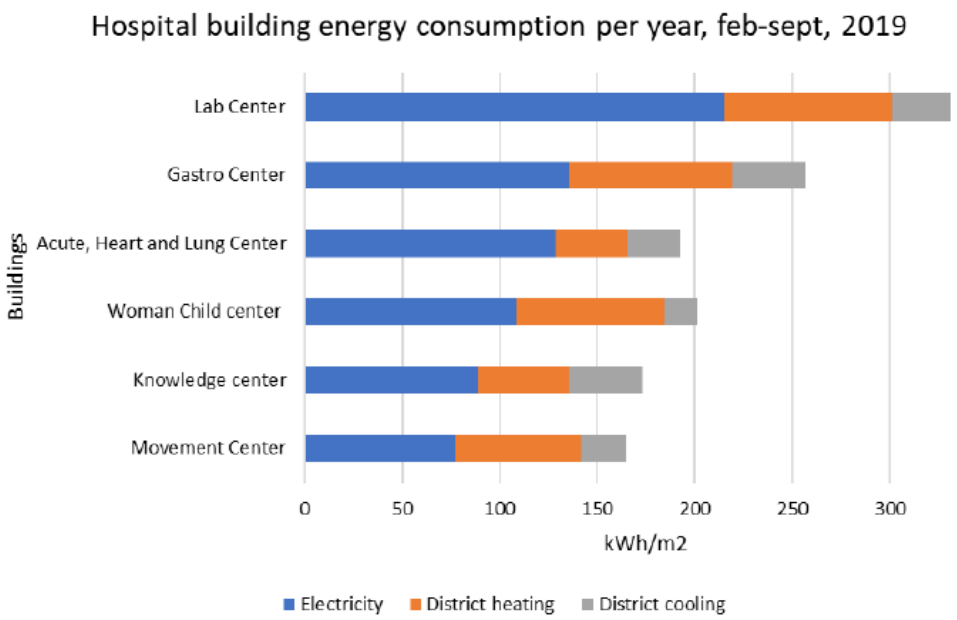
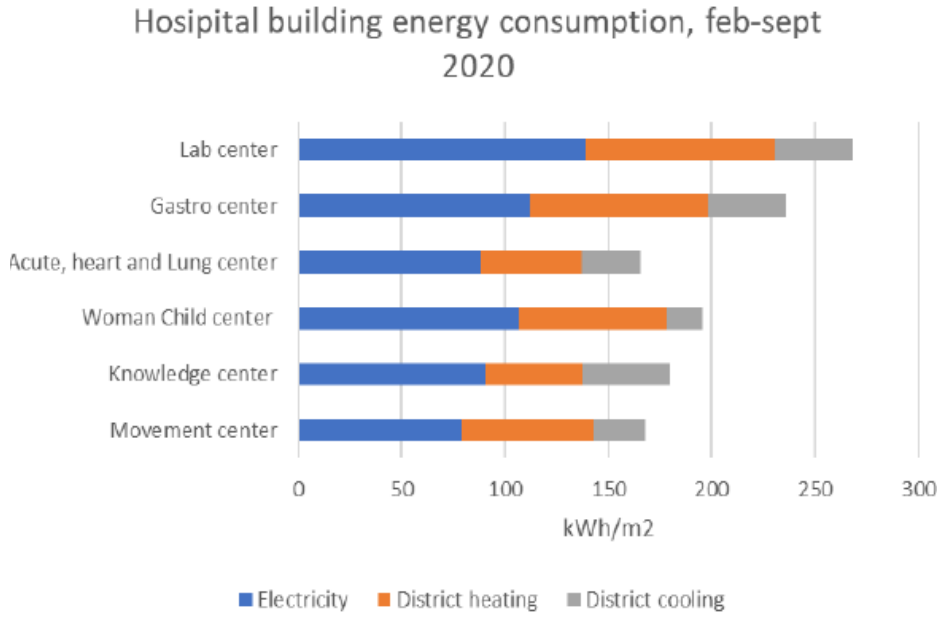
Energy consumption in various buildings at St. Olavs hospital

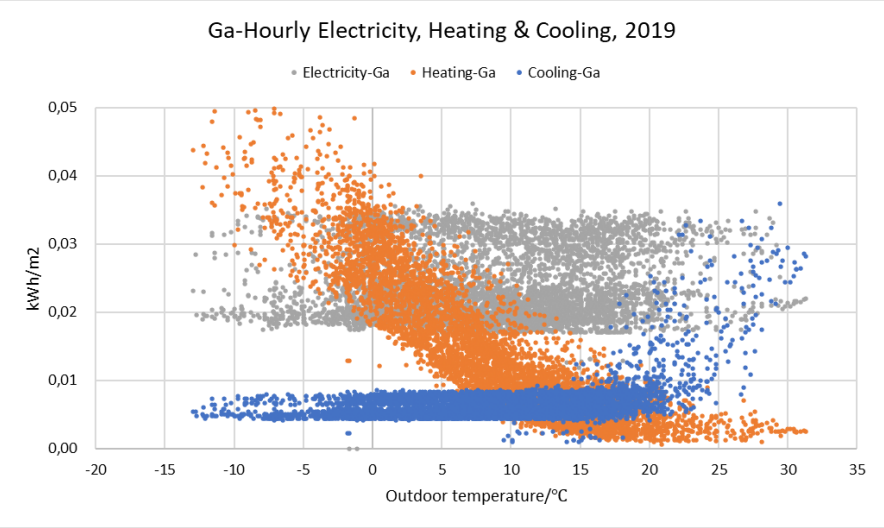


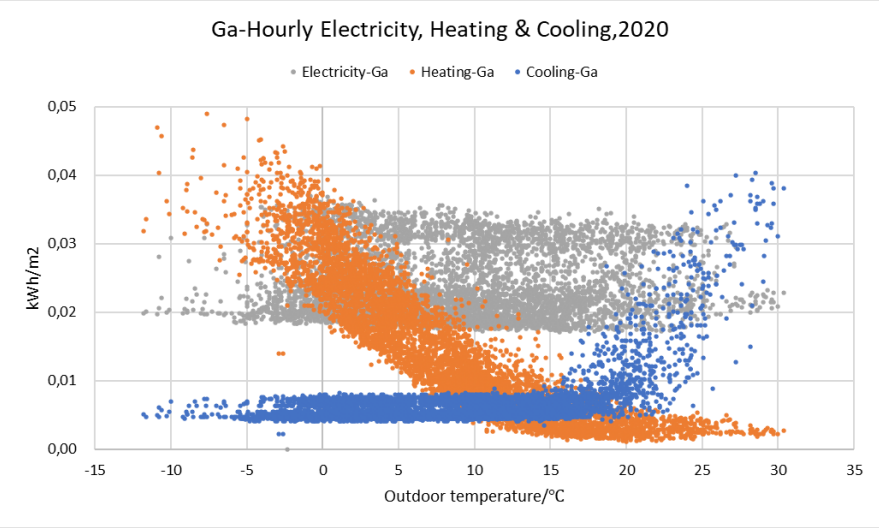


- *Energy consumption for buildings at St. Olavs hospital before the COVID pandemic*

- *Energy consumption for buildings at St. Olavs hospital during the COVID pandemic*

Energy consumption at St. Olavs hospital

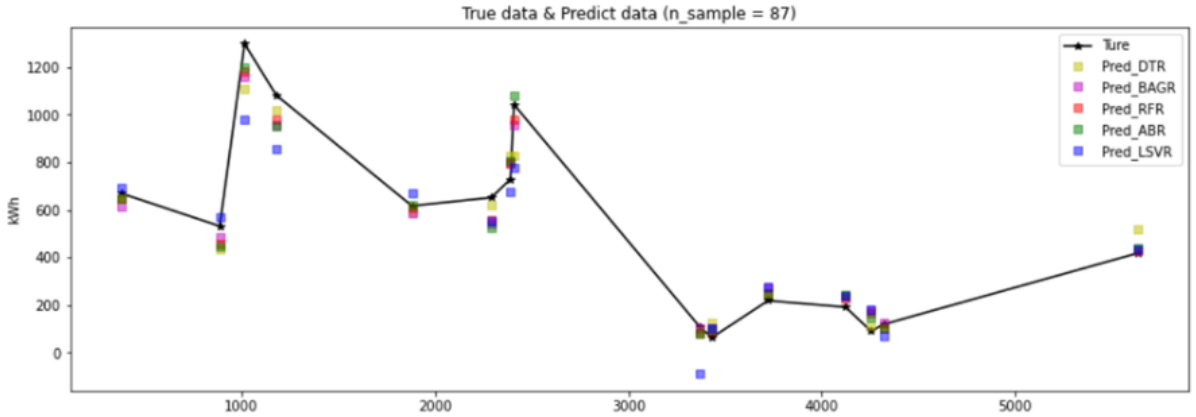




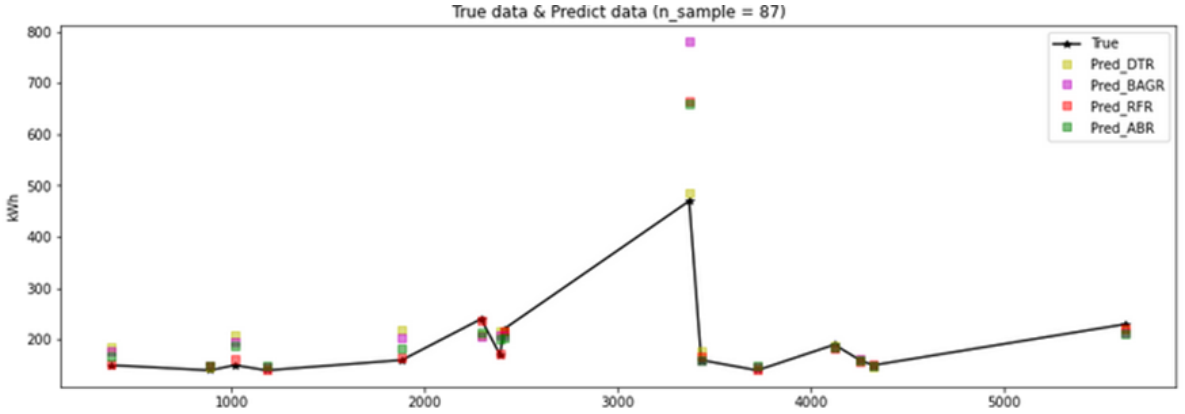
- *Energy consumption for Gastro center at St. Olavs hospital before the COVID pandemic*

- *Energy consumption for Gastro center at St. Olavs hospital during the COVID pandemic*

Energy consumption in Gastro center at St. Olavs hospital



- *Heating energy consumption of Gastro center at St. Olavs hospital during the COVID pandemic*



- *Cooling energy consumption of Gastro center at St. Olavs hospital during the COVID pandemic*

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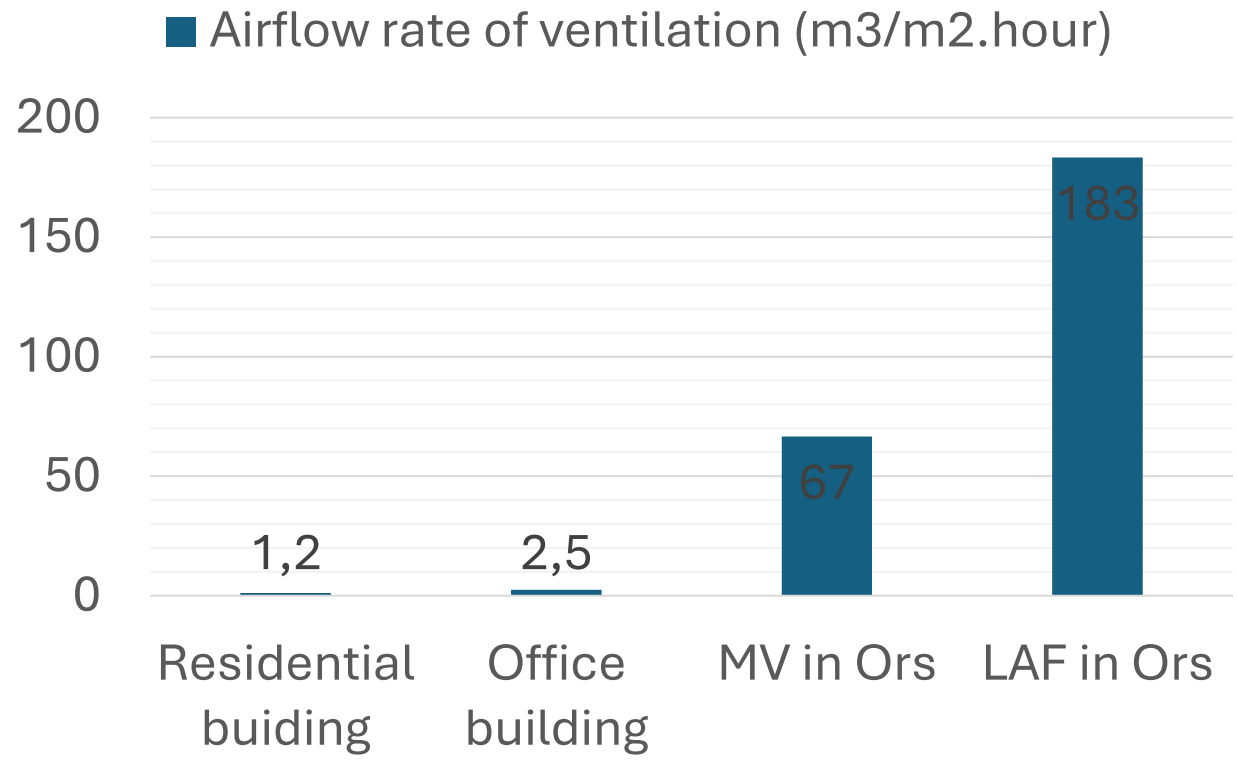
Summary - airflow rate in various buildings



- https://dibk.no/byggereglene/byggteknisk-forskrift-tek17/14/14-2/

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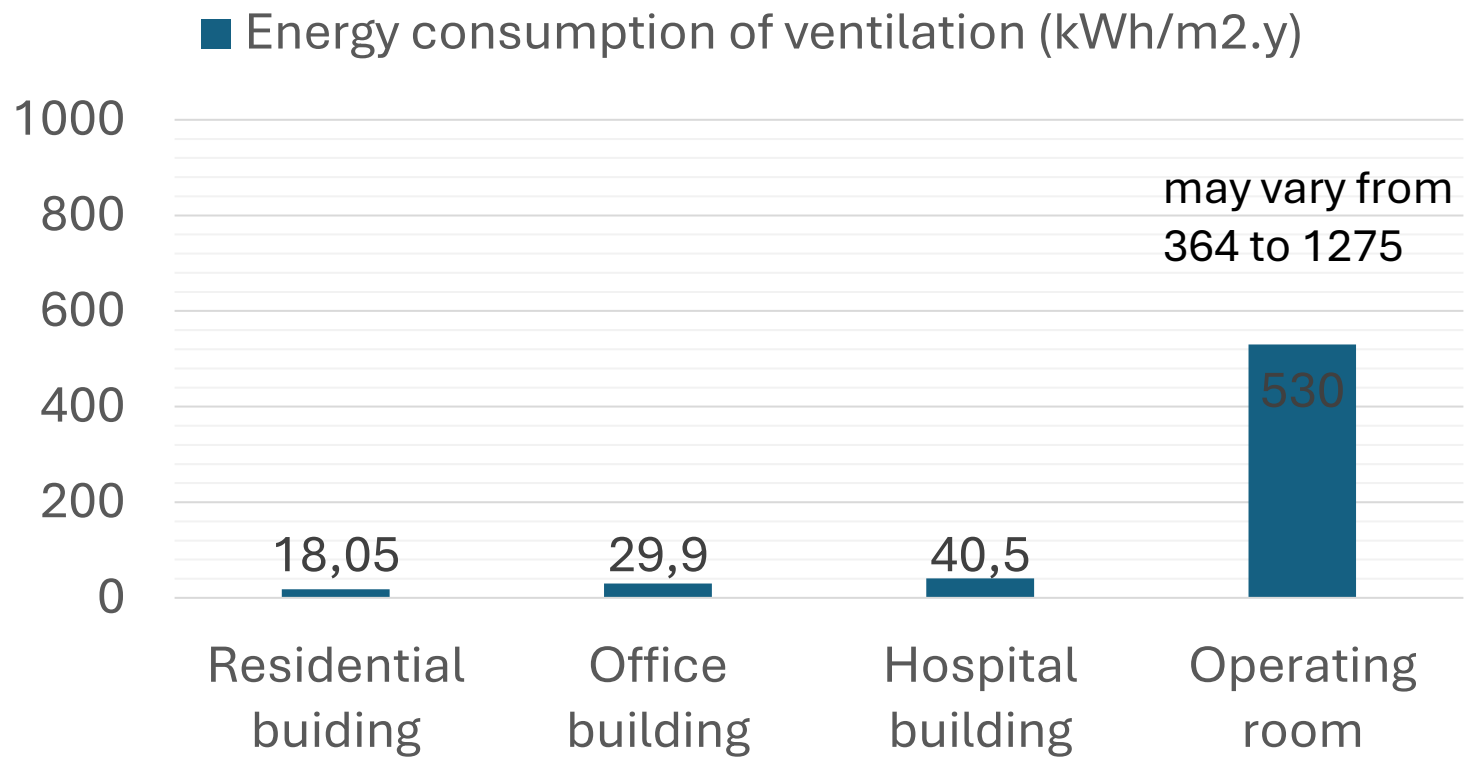
Summary - energy consumption in various buildings



- https://dibk.no/byggereglene/byggteknisk-forskrift-tek17/14/14-2/
- Melhado, M. D. A., Beyer, P. O., Hensen, J. L. M., & Siqueira, L. F. G. (2005). The thermal comfort, the indoor environment control, and the energy consumption in three types of operating rooms. In Building Performance Simulation: a better support for the practice of today and tomorrow?, Proceedings IBPSA-NVL Conference 20 October 2005 (pp. 747-754). Montreal: IBPSA.

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Remarks

- In operating theatres, many factors, including the use of operating lamps, the number of staff, different ventilation systems and supply airflow rate, may influence the local indoor air quality in the operating microenvironment.
- Under certain operating conditions, mixing ventilation may distribute clean air effectively to the operating microenvironment.
- Lower CFU level may be achieved in ORs with Mixing ventilation when using proper surgical clothing with lower activity intensity.
- The location of instrument table may affect the exposure risk of surgical instrument due to airflow distribution.
- The influence of circulating nurses' activities on indoor air quality in operating room may be underestimated.
- Surgical staff suffer more from thermal discomfort in ORs with MV than in LAF.

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Verification phase

We considered two possible approaches for structuring the PhD students' contributions:

1) Dividing students into three groups

- Each group (3–4 PhD candidates) would focus on one of the three research areas. Each PhD student would contribute to either thermal comfort, indoor air quality, or energy efficiency.

2) Developing a matrix-based approach (preferred option)

- Instead of three groups, we would build a matrix that maps different healthcare setups (e.g., hospital operating rooms, patient rooms, other healthcare facilities) to the relevant KPIs.
- This would allow students to focus on specific healthcare environments while ensuring comprehensive KPI coverage.
- Concrete baseline and benchmark values would be established to support the verification methodology.

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

Verification phase

- Literature Review & Research Supervision

- To support this initiative, we propose preparing three literature review articles with input from all PhD students. The preliminary plan is as follows:

- Sasan, Risto, and Guangyu will each lead one of the three research areas or facility type.
- PhD candidates will conduct literature reviews on their selected/assigned topics and provide input of baseline values/benchmark on solidifying the KPIs.
- Training session preparation:
  - Students will review relevant literature before the session.
  - During the session, they will present initial findings.
  - Afterward, we will hold follow-up meetings to refine and complete the literature articles.
  - These literature articles will be included as appendices in the verification methodology document.

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Verification phase

- Before proceeding, we would like to get your feedback and approval from the consortium. If approved, we will distribute relevant literature materials and ask PhD candidates to select their area of focus (e.g., operating rooms, isolation rooms, patient rooms, or other healthcare setups). They will also indicate their research focus within the KPI framework.
- Regular Meetings & Supervision Plan
- Regarding monthly supervision meetings, we agree with your proposed schedule:

- Last Thursday of each month after 5:00 PM
- Each PhD student will present their progress on KPIs and literature reviews during these sessions.
- Please proceed with scheduling these meetings with all PhD candidates and supervisors.

- We look forward to your feedback and approval. If I have missed anything, Risto and Sasan, please feel free to correct or clarify.

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Reference

- Cao, Guangyu; Pedersen, Christoffer; Zhang, Yixian; Drangsholt, Finn; Radtke, Andreas; Langvatn, Håkon; Stenstad, Liv-Inger; Mathisen, Hans Martin; Skogås, Jan Gunnar. Can clothing systems and human activities in operating rooms with mixing ventilation systems help achieve 10 CFU/m3 level during orthopaedic surgeries?. Journal of Hospital Infection 2021
- Amar Aganovic, Guangyu Cao, Evaluation of airborne contaminant exposure in a single-bed isolation ward equipped with a protected occupied zone ventilation system, First Published January 3, 2019, https://doi.org/10.1177/1420326X18823048. Indoor and Built Environment.
- Guangyu Cao, Anders M. Nilssen, Zhu Cheng, Liv-Inger Stenstad, Andreas Radtke, Jan Gunnar Skogås. Laminar airflow ventilation and mixing ventilation: which is better for operating rooms regarding airflow distribution near an orthopedic surgical patient? American Journal of Infection Control, accepted November 27th 2018.
- Cao GY, Storås M, Aganovic A, Stenstad LI. Skogås JG. 2018. Do surgeons and surgical facilities disturb the clean air distribution close to a surgical patient in an orthopedic operating room with laminar airflow? American Journal of Infection Control, 2018 (October) Volume 46, Issue 10, Pages 1115-1122. DOI: https:doi.org/10.1016/j.ajic.2018.03.019
- Aganovic A, Cao GY, Stenstad LI. Skogås JG, Mathisen HM (2017) Impact of surgical lights on the velocity distribution and airborne contamination level in an operating room with laminar airflow. Building and Environment. Volume 126, December 2017, Pages 42-53
- Masab Khalid Annaqeeb, Yixian Zhang, Jakub Wladyslaw Dziedzic, Kai Xue, Christoffer Pedersen, Liv-Inger Stenstad, Vojislav Novakovic, Guangyu Cao. Influence of the surgical team activity on airborne bacterial distribution in the operating room with mixing ventilation system: A case study at St. Olavs Hospital. The Journal of Hospital infection. 2021, 116:91-98. Published: August 14, 2021. DOI:https://doi.org/10.1016/j.jhin.2021.08.009.
- Kai Xue, Md. Uzzal Hossain, Meng Liu *, Mingjun Ma, Yizhi Zhang, Mengqiang Hu, XiaoYi Chen, Guangyu Cao. BIM Integrated LCA for Promoting Circular Economy towards Sustainable Construction: An Analytical Review" 2021. Sustainability. Sustainability 2021, 13(3), 1310; https://doi.org/10.3390/su13031310
- Minchao Fan; Guangyu Cao; Christoffer Pedersen; Shilei Lu; Liv-Inger Stenstad; Jan Gunnar Skogås. Suitability evaluation on laminar airflow and mixing airflow distribution strategies in operating rooms: A case study at St. Olavs Hospital. Building and Environment (IF 4.971) Pub Date : 2021-02-12 , DOI: 10.1016/j.buildenv.2021.107677. Volume 194, May 2021, 107677. (This article distinguish the difference of indoor air quality in operating rooms with two different ventilation systems.)
- Cheng, Z., Aganovic, A., Cao, G. et al. Experimental and simulated evaluations of airborne contaminant exposure in a room with a modified localized laminar airflow system. Environ Sci Pollut Res 28, 30642–30663 (2021). https://doi.org/10.1007/s11356-021-12685-4

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