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# One Operating Room, Two Thermal Worlds: Determinants and Limits of Thermal Comfort for Surgical Staff

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**Abstract**

Thermal comfort in operating rooms is critical for staff performance and safety, but conflicting requirements among professional groups create complex challenges. In a real operating room with a unidirectional airflow system, air velocity and temperature were measured, and predicted thermal sensation as well as the proportion of dissatisfied staff were calculated according to international standards. Analyses included surgeons, technical assistants, and anesthesiologists, considering clothing insulation, task-specific activity, gender, body mass index, and the use of lead aprons of different weights. Gender, body mass index, and temperature strongly influenced thermal comfort, whereas variation in air velocity had only minor effects. Thermal comfort targets diverged markedly between professional groups. Under identical conditions in our operating room, up to 75% of male surgeons wearing lead aprons experienced pronounced heat stress, whereas approximately 22% of female anesthesiologists experienced predominantly cold discomfort. Female surgeons would require temperatures as low as 16 °C to achieve thermal comfort, while nearly 50% of male surgeons perceived even this temperature as uncomfortably warm. Removing lead aprons reduced heat stress in surgeons but increased cold stress in anesthesiologists. Higher body-mass index improved heat dissipation in surgeons but aggravated cold stress in anesthesiologists. These findings demonstrate that uniform temperature settings cannot ensure thermal comfort for all professional groups. Practical implications include the need for role-specific strategies, such as targeted personal cooling or warming measures and differentiated clothing systems, to improve working conditions and maintain patient safety in operating rooms.

**Keywords:** thermal comfort; operating room; surgical staff; PMV–PPD model; airflow; heat stress; protective clothing

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Academic Editor: Amirul Khan

Received: 26 March 2026
Revised: 8 May 2026
Accepted: 11 May 2026
Published: 15 May 2026



## 1. Introduction

Thermal conditions in operating rooms (ORs) must simultaneously ensure patient safety, infection control, and adequate working conditions for staff [1]. However, these requirements create a fundamental conflict: while relatively low ambient temperatures are required to support surgeons performing physically demanding tasks under insulating protective clothing [2], the same conditions frequently induce pronounced cold discomfort in anesthesiologists and other less active staff. Consequently, thermal perception differs substantially between professional groups exposed to the same environment [2,3].

Prolonged exposure to non-optimal thermal conditions has been associated with relevant physiological and cognitive effects in occupational settings [4,5]. In ORs, heat-related strain may lead to dehydration, cardiovascular load, and impaired performance, including reduced cognitive function and an increased risk of errors [6,7]. These effects are particularly critical in surgical environments, where even minor impairments may affect procedural accuracy and patient safety [8]. In addition, excessive sweating may increase the risk of contamination of the surgical field [9,10]. Conversely, cold-related discomfort may impair concentration and manual performance in less active staff [5]. Thus, both heat- and cold-related thermal strain represent relevant risk factors for staff well-being and clinical outcomes.

To reduce heat-related strain among surgical staff, relatively low ambient air temperatures have long been proposed. Early experimental work by Wyon et al. (1968) [11] suggested temperatures around 19 $\pm$ 1 °C as beneficial under OR conditions. Similar temperature ranges have been reported in more recent studies [2,12] and are reflected in current guidelines and standards in several countries [13]. However, such low temperatures pose significant challenges for patients, as anesthesia impairs thermoregulation and awake patients frequently experience pronounced thermal discomfort [14]. Consequently, additional measures such as forced-air warming or fluid warming systems are required to maintain normothermia; nevertheless, achieving the World Health Organization-recommended core body temperature of at least 36 °C remains challenging in clinical practice [15,16]. In addition, cold-related discomfort is commonly reported by anesthesiologists and non-sterile technical staff, who are exposed to lower activity levels and reduced clothing insulation compared with surgical personnel [17–19].

Despite these well-documented challenges, a systematic understanding of the underlying factors driving these differences remains limited, particularly with respect to their quantitative interaction. In particular, the relative contribution of environmental conditions, metabolic rate, clothing insulation, and individual characteristics to thermal perception in ORs has not been comprehensively quantified.

Field-based studies have consistently reported divergence in thermal perception between professional groups over several decades. Early investigations from 1968 described increased cold discomfort among anesthesiology staff compared with heat strain experienced by surgeons [11]. These findings have been confirmed in subsequent studies under real OR conditions [9,17,19]. In addition, survey-based research has identified multiple influencing factors on perioperative thermal comfort, including activity level, clothing, environmental conditions, and organizational aspects [20]. However, these studies are predominantly based on subjective assessments or observational data and therefore do not allow a structured, quantitative analysis of the relative contribution of individual influencing factors to thermal perception. In particular, the combined effects of protective clothing (e.g., vapor-impermeable lead aprons with a weight up to 13 kg), metabolic differences between professional groups, and individual characteristics such as sex and body mass index have not yet been systematically quantified within a unified analytical framework. Consequently, the magnitude of the observed differences and the relative importance of individual parameters remain insufficiently understood.

To systematically analyze thermal conditions in ORs, a structured assessment of environmental parameters and their interaction with human factors is required. A widely used approach for this purpose is the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) model, originally developed by Fanger [21] and incorporated into the international standard ISO 7730 [22]. The PMV–PPD model combines environmental parameters (air temperature, air velocity, mean radiant temperature, and relative humidity) with personal factors such as metabolic rate and clothing insulation to estimate the average thermal sensation of a group under steady-state conditions [21,22]. Metabolic rate is typically determined based on standardized methods such as ISO 8996 [23], while anthropometric parameters (e.g., body surface area) can be derived according to DIN 33402-2 [24]. Individual characteristics such as sex or body mass index are not direct input parameters of the model but may indirectly influence thermal responses through their effects on metabolic rate and body composition.

In contrast to predominantly descriptive and survey-based field studies, this modeling approach enables a structured and quantitative assessment of the relative contribution of individual parameters by systematically varying environmental and personal input variables under controlled conditions.

Despite known limitations, particularly in non-uniform and transient environments such as ORs, the PMV–PPD approach provides a standardized and widely applied framework for comparative thermal assessments in indoor environments [22]. In this study, it is therefore used as a model-based screening tool to evaluate differences in thermal conditions between professional groups rather than to predict individual thermal perception under real clinical conditions.

The PMV index describes the average thermal sensation of a group on a seven-point scale ranging from −3 (cold) to +3 (hot), with 0 indicating thermal neutrality [21,22]. Based on the PMV, the PPD estimates the proportion of individuals likely to perceive the thermal environment as unacceptable [21,22]. Even under conditions close to thermal neutrality, a certain proportion of occupants is expected to remain dissatisfied due to interindividual variability. According to ISO 7730, a PPD $\leq$ 10% corresponds to indoor environmental quality Category II (moderate expectation level), which is commonly considered an acceptable target range for typical indoor environments [22].

The aim of this study was to perform a model-based, quantitative assessment of thermal conditions for surgeons, anesthesiologists, and technical assistants in ORs using the PMV–PPD approach. The analysis considered relevant environmental parameters (e.g., air temperature and air velocity) as well as personal factors such as metabolic rate and clothing insulation, representing typical working conditions of different professional groups. In addition, OR-specific factors—most notably the use of heavy, vapor-impermeable lead aprons—were explicitly incorporated into the analysis, allowing their combined impact on metabolic rate and clothing insulation to be assessed. Furthermore, the study integrates the influence of sex and body mass index in a structured manner, thereby extending previous approaches that typically consider only selected parameters in isolation. Based on this approach, the study aims to identify and compare conflicting thermal requirements between these groups and to provide a quantitative estimate of the relative contribution of key influencing factors under standardized conditions. In doing so, the study extends existing field-based observations by moving from qualitative description toward a structured, model-based quantification of interacting parameters.

## 2. Materials and Methods

This study was performed in a German university hospital. The need for ethical approval was waived by the local ethics committee, as neither humans nor animals were directly investigated, and all analyses were based on environmental measurements and subsequent standardized calculations.

## 2.1. Experimental Setting

All measurements were conducted in an OR with dimensions of 7.04 × 6.95 × 3.00 m, equipped with a ceiling-mounted unidirectional displacement flow (UDF) ventilation system. The system comprised a centrally located "protective zone" beneath a 3.2 × 3.2 m air supply outlet and a surrounding peripheral zone. The total supply air volume flow rate was set to 9000 $m^3/h$. Due to lower flow resistance in the central area of the laminar airflow field, air velocities were slightly higher in the center compared to the periphery. Exhaust air outlets were located in each corner of the OR. At the geometric center of the ceiling outlet, a ceiling-mounted column with three articulated arms (Getinge AB, Gothenburg, Sweden) was installed. These supported two surgical lights (Maquet Power LED II, Getinge, Ardon, France) and one monitor (0.63 × 0.40 m).

Measurements were performed within the protective zone to assess the parameters of the unidirectional airflow and their influence on thermal conditions. Initial measurements were conducted under "at rest" (empty-room) conditions in accordance with ISO 14644 [25] and DIN 1946-4 [13], with no equipment positioned within the protected area. Subsequently, the surgical lights and monitor were arranged in three representative configurations (scenarios A–C), reflecting typical intraoperative setups (Figure 1).

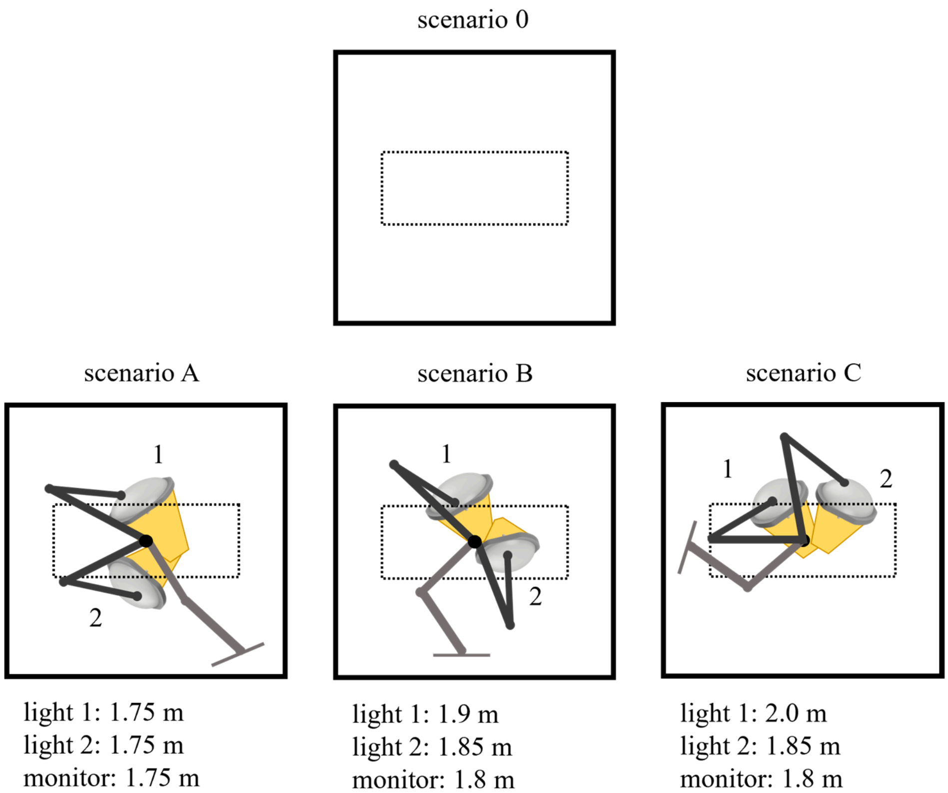


**Figure 1.** Schematic overview of the investigated operating room configurations within the protected zone beneath the unidirectional airflow ceiling. Scenario 0 represents the empty-room condition with the operating table indicated by dashed lines. Scenarios A–C show three typical arrangements of two surgical lights and one monitor above the operating table. All configurations are displayed within the protected zone, including the vertical positioning of the devices.

Air velocity and air temperature were measured using ten calibrated hot-wire anemometer probes (Testo SE & Co. KGaA, Lenzkirch, Germany), mounted on a horizontal rod with a spacing of 0.3 m. The measurement assembly was positioned at a height of 1.2 m and moved horizontally across the OR in increments of 0.30 m, resulting in a regular measurement grid. The probes were connected to three control units (Testo 350-M/XL, Titisee-Neustadt, Germany) to enable simultaneous data acquisition. To account for undirectional airflow effects, measurements were repeated with the probe array rotated by 90°. Data acquisition was performed on three separate days, each including all defined scenarios (Figure 1).

The investigated OR was equipped with a UDF system generating a vertically directed airflow within the protected zone. Across all investigated configurations, air temperature measurements within the protected area showed only minor spatial variation (20.1 ± 0.6 °C to 20.7 ± 0.6 °C), supporting the use of averaged environmental parameters for this comparative screening-level PMV–PPD analysis.

### *2.2. Parameters for Thermal Comfort Assessment*

For the calculation of individual thermal comfort levels of male and female OR staff from the three professional groups (surgeons, sterile-dressed technical assistants, and anesthesiologists), the PMV–PPD model according to ISO 7730 was applied [22]. The selection and calculation of thermal comfort parameters were based on the applicable international standards described below. However, in order to enable a standardized comparative screening assessment under reproducible operating-room conditions, several methodological simplifications, assumptions, and averaging procedures were intentionally applied. In particular, mean radiant temperature was not directly measured and was approximated by air temperature for the PMV–PPD calculations.

Environmental input parameters included air velocity and air temperature, which were derived from the measurements described above [25]. Mean values and standard deviations were calculated across all measurement positions. For the purpose of this comparative screening analysis, mean radiant temperature was not directly measured and was approximated by air temperature as a simplifying assumption within the PMV–PPD calculations. Relative humidity was assumed to be constant at 50%, representing a typical value within the recommended range of the standard [22]. These assumptions were intentionally introduced to enable a standardized and reproducible screening-level comparison of thermal conditions between professional groups under controlled operating-room conditions.

Personal parameters comprised metabolic rate (M) and clothing insulation (Icl). Metabolic rate was estimated according to ISO 8996 based on task-specific activity levels and working postures (e.g., standing, bending, sitting) [23]. To account for interindividual variability, values were normalized to the reference metabolic rate of 58.2 $W \cdot m^{-2}$ and adjusted using anthropometric parameters. Body surface area was calculated from body height and mass in accordance with DIN 33402-2 [24]. The resulting metabolic rate assumptions are summarized in Table 1. Clothing insulation values were assigned based on ISO 9920, reflecting typical clothing ensembles for each professional group, and are presented in Table 2 [26].

Representative body characteristics were defined for three BMI categories (normal weight, pre-obese, and obesity class I) for male and female individuals. Sex-specific differences were thus considered indirectly through their influence on body mass, height, and resulting metabolic heat production, rather than as explicit input parameters of the PMV model [27].

In addition, the use of lead aprons (mean mass: 7.5 kg, range: 3–13 kg) was included as an OR-specific factor influencing thermal insulation and metabolic load. Clothing insulation values were approximated based on comparable garments according to ISO 9920, as described by König et al. [28].

All input parameters used for PMV and PPD calculations are summarized in Table 3.

**Table 1.** Metabolic rate (M) values used for PMV–PPD calculations based on ISO 9920 [26] and ISO 8996 [23]. Metabolic rate values represent standardized estimates derived from task-specific activity classifications (posture, movement intensity, and workload) for each professional group.

<table>
<tr><td colspan="3">ISO 8996:2022 Annex A Evaluation of the metabolic rate at level 1, Screening</td></tr>
<tr><td>Class</td><td>Range of metabolic rates: Examples [W]</td><td>Examples</td></tr>
<tr><td>1: Low metabolic rate</td><td>125 to 235</td><td>sedentary activity; standing, light activity; light arm and leg work</td></tr>
<tr><td>2: Moderate metabolic rate</td><td>235 to 360</td><td>sustained hand and arm work; arm and leg work; arm and trunk work (work with pneumatic hammer);</td></tr>
<tr><td colspan="3">The arithmetic mean of 235 W and 360 W was calculated as 297.5 W for further analysis.</td></tr>
<tr><td colspan="3">ISO 8996:2022 Table B.3 Increase ΔM (W) of the metabolic rate estimated due to body postures</td></tr>
<tr><td>Body posture</td><td>ΔM [W]</td><td>professions</td></tr>
<tr><td>sitting</td><td>0</td><td>anesthesiologists</td></tr>
<tr><td>standing</td><td>25</td><td>technical assistants</td></tr>
<tr><td>standing stooped</td><td>2</td><td>surgeon</td></tr>
<tr><td colspan="3">ISO 8996:2022 Table B.1: Analysis of the effect of lead apron weight of metabolic rate M [W]</td></tr>
<tr><td>load carried by the person L [kg]</td><td>M [W]</td><td>formular for the evaluation of the metabolic rate M [W] when lifting</td></tr>
<tr><td>3</td><td>11</td><td rowspan="3">Idle (sit/stand) and hold<br>$M = M_0 + (4.12 + L)$</td></tr>
<tr><td>7.5</td><td>30</td></tr>
<tr><td>13</td><td>52</td></tr>
<tr><td colspan="3">EXAMPLE for surgeon male/female</td></tr>
<tr><td>gender</td><td>M [met]</td><td>formular for the metabolic rate</td></tr>
<tr><td>male</td><td>2.94</td><td>$M = (297.5\ W/1.946\ m^2)/58.15\ W/m^2$</td></tr>
<tr><td>female</td><td>1.96</td><td>$M = (297.5\ W/1.708\ m^2)/58.15\ W/m^2$</td></tr>
<tr><td colspan="3">general formula: $M = (\text{metabolic rate } [W]/\text{Adu } [m^2])/58.15\ W/m^2$</td></tr>
</table>

### *2.3. Calculation of Thermal Comfort (PMV–PPD Model)*

Thermal comfort was quantified using the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices in accordance with ISO 7730:2025 [22]. The assessment was based on standardized environmental and personal input parameters as described above. Due to the predominantly static working postures of the investigated professional groups during operative procedures, the combined effects of body movement and relative air velocity on clothing insulation were not additionally modeled. Accordingly, the present analysis represents a simplified comparative screening approach under standardized OR conditions.

To support the plausibility of the modeling approach, the selected input parameters and resulting thermal patterns were qualitatively compared with trends reported in previous field-based studies on thermal comfort in ORs.

**Table 2.** Calculation of clothing thermal insulation (Icl) for operating room personnel based on individual garment insulation values according to ISO 9920 [26]. Clothing ensembles are described item by item (e.g., underwear, scrubs, sterile gown, footwear, gloves), and the resulting total insulation is calculated for each professional group. For lead aprons, no standardized insulation values are available due to their vapor-impermeable and compressive material properties. Therefore, an approximate Icl value was derived based on comparable impermeable garment types (e.g., rain-protective jackets and coats below knee length) according to ISO 9920 [26], resulting in an estimated insulation of 0.44 Icl.

<table>
<tr><th rowspan="2">Clothing</th><th>ISO 9920</th><th colspan="2">Surgeon</th><th colspan="2">Technical Assistants</th><th colspan="2">Anesthesiologists</th></tr>
<tr><th>Icl</th><th></th><th>Lead Apron</th><th></th><th>Lead Apron</th><th></th><th>Lead Apron</th></tr>
<tr><td>panties/panties and bra</td><td>0.03</td><td colspan="6" rowspan="6">0.48</td></tr>
<tr><td>short sleeves</td><td>0.15</td></tr>
<tr><td>trousers, normal</td><td>0.25</td></tr>
<tr><td>socks ankle-length</td><td>0.02</td></tr>
<tr><td>Shoes</td><td>0.02</td></tr>
<tr><td>face mask and hood</td><td>0.01</td></tr>
<tr><td>MIN lead apron (rain-protective jacket)</td><td>0.31</td><td></td><td rowspan="2">0.44</td><td></td><td rowspan="2">0.44</td><td></td><td rowspan="2">0.44</td></tr>
<tr><td>MAX lead apron (coat, below knee length)</td><td>0.56</td><td></td><td></td><td></td></tr>
<tr><td>sterile gown (work smock, below knee length)</td><td>0.36</td><td>0.36</td><td>0.36</td><td>0.36</td><td>0.36</td><td></td><td></td></tr>
<tr><td>gloves</td><td>0.05</td><td>0.05</td><td>0.05</td><td>0.05</td><td>0.05</td><td></td><td></td></tr>
<tr><td>seat/stool</td><td>0.01</td><td></td><td></td><td></td><td></td><td>0.01</td><td>0.01</td></tr>
<tr><td></td><td>X-Icl</td><td>0.89</td><td>1.33</td><td>0.89</td><td>1.33</td><td>0.49</td><td>0.93</td></tr>
<tr><td>additional jackets (work jacket)</td><td>0.26</td><td></td><td></td><td></td><td></td><td>0.75</td><td>1.19</td></tr>
<tr><td>additional pants (long-legged) and shirt (long sleeves)</td><td>0.22</td><td></td><td></td><td></td><td></td><td>0.97</td><td>1.41</td></tr>
</table>

**Table 3.** Input parameters for thermal comfort calculations, including metabolic rate (M) and clothing insulation (Icl) for surgeons, sterile-dressed technical assistants, and anesthesiologists. Values were assigned according to ISO 8996 (metabolic rate) and ISO 9920 (clothing insulation).

<table>
<tr><th colspan="2">Profession</th><th colspan="2">Surgeons</th><th colspan="2">Technical Assistants</th><th colspan="2">Anesthesiologists</th></tr>
<tr><td colspan="2">lead apron</td><td></td><td>+yes</td><td></td><td>yes</td><td></td><td>yes</td></tr>
<tr><td rowspan="2">metabolic rates of gender</td><td>male [M]</td><td>2.94</td><td>3.20</td><td>2.85</td><td>3.11</td><td>1.10</td><td>1.24</td></tr>
<tr><td>female [M]</td><td>1.96</td><td>2.13</td><td>1.90</td><td>2.08</td><td>0.74</td><td>0.89</td></tr>
<tr><td colspan="2">clothing insulation values [Icl]</td><td>0.89</td><td>1.33</td><td>0.89</td><td>1.33</td><td>0.49</td><td>0.93</td></tr>
<tr><td colspan="6">additional jacket for anesthesiologists [Icl]</td><td>0.75</td><td>1.19</td></tr>
<tr><td colspan="6">additional jacket and long underwear for anesthesiologists [Icl]</td><td>0.97</td><td>1.41</td></tr>
</table>

### *2.4. Statistical Analysis*

Differences in thermal conditions between professional groups were analyzed based on the calculated PPD values. The analysis was based on scenario-specific PMV–PPD calculations derived from combinations of environmental and personal input parameters, as described above. Each parameter combination was treated as an independent sample unit for comparative analysis. For each professional group, mean values and standard deviations of PPD were calculated across all simulated scenarios. The distribution of PPD values was assessed using normal Q–Q plots and the Shapiro–Wilk test. Group differences were evaluated using independent-samples *t*-tests [29]. To account for multiple comparisons, *p*-values were adjusted using the Holm Bonferroni method. A significance level of $p < 0.05$ was considered statistically significant. The applied statistical approach is intended to support structured comparisons of model-based thermal conditions between professional groups rather than to infer population-based variability.

## 3. Results

### 3.1. Environmental Conditions and Airflow Characteristics in the OR

All measurements were conducted under controlled indoor conditions in a mechanically ventilated OR. Environmental parameters such as air temperature and air velocity were regulated by the ventilation system in accordance with applicable standards and can therefore be considered independent of external meteorological influences. The measured values served as input parameters for the subsequent PMV–PPD calculations.

Air velocity and air temperature within the OR were normally distributed and did not differ significantly between the empty-room condition and configurations including surgical lights and a monitor (Figure 1). Mean air velocity was $0.278 \pm 0.07$ m·s$^{-1}$ in the empty-room condition and $0.273 \pm 0.09$ m·s$^{-1}$ in scenarios A–C ($p = 0.927$), while air temperature increased slightly from $20.1 \pm 0.6$ °C to $20.7 \pm 0.6$ °C without reaching statistical significance ($p = 0.081$).

In contrast, the uniformity of velocity was significantly reduced when surgical lights and the monitor were positioned within the protected zone, decreasing from 91 ± 11% in 'at rest' condition to 78 ± 15% in scenarios A–C ($p < 0.001$).

### 3.2. Thermal Comfort of OR Staff

Thermal comfort differed markedly between professional groups and sexes under identical environmental conditions. Thermal sensation was assessed using the PMV index, and corresponding PPD values were derived to quantify the proportion of dissatisfied individuals. At a mean air velocity of 0.28 m·s$^{-1}$ and a temperature of 20.5 °C, male surgeons with pre-obese BMI wearing 7.5 kg lead aprons showed pronounced heat-related thermal dissatisfaction (PPD 75 ± 0.9%), indicating that three out of four perceived the environment as too warm. In contrast, anesthesiologists exhibited an opposite response pattern under the same conditions. Female anesthesiologists showed lower overall dissatisfaction (PPD 22 ± 2.5%); however, this dissatisfaction was predominantly associated with cold-related discomfort, indicating a perception of the environment as too cool. These findings highlight that identical environmental conditions can induce opposing thermal perceptions between professional groups. The differences were statistically significant ($p < 0.001$) (Figure 2).

Without lead aprons, male surgeons still reported substantial heat-related dissatisfaction (PPD 47 ± 1.9%), whereas anesthesiologists exhibited the opposite pattern: female anesthesiologists showed very high levels of cold-related discomfort (PPD 99 ± 0.5%) under identical conditions ($p < 0.001$).

The lowest levels of thermal dissatisfaction were observed in teams without lead aprons. Female surgeons (PPD 9 ± 0.9%) and sterile-dressed female technical assistants (PPD 8 ± 0.8%) were predominantly within the comfort range, while male anesthesiologists experienced mild cold-related discomfort (PPD 20 ± 2.9%).

https://doi.org/10.3390/atmos17050503

| | | profession | PMV x | PMV s | PPD [%] x | PPD [%] s |
|---|---|---|---|---|---|---|
| male | | surgeons | **1.4** | 0.04 | **47** | 1.91 |
| male | | technical assistants | **1.3** | 0.04 | **42** | 1.90 |
| male | | anesthesiologists | **−0.8** | 0.08 | **20** | 2.90 |
| male | leap apron | surgeons | **2.0** | 0.02 | **75** | 0.91 |
| male | leap apron | technical assistants | **1.9** | 0.02 | **71** | 0.97 |
| male | leap apron | anesthesiologists | **0.1** | 0.04 | **5** | 0.27 |
| female | | surgeons | **0.5** | 0.05 | **9** | 0.93 |
| female | | technical assistants | **0.4** | 0.05 | **8** | 0.82 |
| female | | anesthesiologists | **−3.2** | 0.14 | **99** | 0.45 |
| female | leap apron | surgeons | **1.0** | 0.03 | **27** | 1.10 |
| female | leap apron | technical assistants | **1.0** | 0.03 | **25** | 1.08 |
| female | leap apron | anesthesiologists | **−0.9** | 0.07 | **22** | 2.51 |

| 7-point of PMV scale | |
|---|---|
| 3 | Hot |
| 2 | Warm |
| 1 | Slightly warm |
| 0 | Neutral |
| −1 | Slightly cool |
| −2 | Cool |
| −3 | Cold |

**Figure 2.** Mean values (x) and standard deviations (s) of predicted mean vote (PMV) and percentage of dissatisfied (PPD) for male and female operating room staff under identical environmental conditions. PMV values describe the direction and magnitude of thermal sensation (positive values indicating warm perception, negative values indicating cool perception), while PPD represents the corresponding proportion of dissatisfied individuals. The combined visualization of PMV and PPD was intentionally chosen to illustrate opposing thermal perceptions between professional groups under identical conditions and to provide an intuitive interpretation of thermal dissatisfaction for clinical application. Conditions: pre-obese body mass index and use of lead aprons (7.5 kg).

The introduction of 7.5 kg lead aprons consistently increased heat-related dissatisfaction in operative staff, including female surgeons (PPD 27 ± 1.1%) and female technical assistants (PPD 25 ± 1.1%). In contrast, anesthesiologists were less affected by this change, with male anesthesiologists remaining largely within the comfort range (PPD 5 ± 0.3%).

When comparing professional groups, sterile-dressed technical assistants showed slightly lower thermal dissatisfaction than surgeons, with differences of up to 2% for women and up to 5% for men. This difference is likely attributable to lower metabolic rates associated with their activity profiles (see Table 1), while the insulating effect of sterile clothing affected both groups similarly.

These findings further underline that identical environmental conditions result in systematically different thermal responses depending on professional role and task-specific activity.

### *3.3. Influence of Airflow Velocity on Thermal Comfort*

Across all professional groups, airflow velocity influenced thermal dissatisfaction differently. While the magnitude of the effect was relatively small, clear group-specific response patterns were observed.

Increasing air velocity from 0.10 to 0.28 m·s$^{-1}$ led to a modest improvement in thermal comfort among surgeons of both sexes. Thermal dissatisfaction decreased by approximately 4–8% PPD compared with low air velocity, independent of lead apron use (with 7.5 kg lead aprons: women 31 vs. 26%, men 79 vs. 75%; without lead aprons: women 14 vs. 9%, men 54 vs. 46%).

In contrast, anesthesiologists exhibited an opposite response pattern. Higher air velocity resulted in a slight increase in thermal dissatisfaction, corresponding to enhanced cold-related discomfort. Compared with 0.10 m·s$^{-1}$, air velocities of 0.28 m·s$^{-1}$ increased PPD by approximately 2–10% (with lead aprons: women 13 vs. 22%, men 7 vs. 5%; without lead aprons: women 96 vs. 100%, men 10 vs. 20%) (Figure 3).

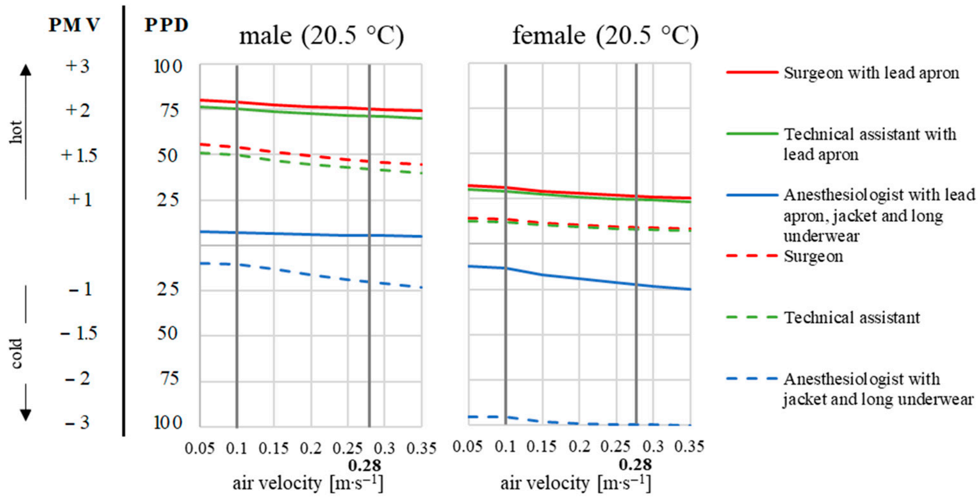


**Figure 3.** Percentage of thermally dissatisfied staff (PPD, 0–100%) as a function of air velocity (0.05–0.35 m·s$^{-1}$) for female and male operating room personnel with a pre-obese BMI. Results are stratified by professional group (surgeons, sterile-dressed technical assistants, and anesthesiologists) and by absence or presence of lead aprons (7.5 kg). Increasing air velocity was associated with a modest reduction in heat-related dissatisfaction among surgical staff, whereas cold-related dissatisfaction slightly increased among anesthesiologists under identical conditions. Vertical lines indicate the range of air velocities measured within the protected zone under real operating-room conditions. PPD values are shown as absolute positive percentages. Graphical positioning above or below the x-axis is used solely to indicate the direction of PMV-derived thermal sensation (heat-related vs. cold-related discomfort) and does not represent negative PPD values.

Overall, these results indicate that increasing airflow velocity has only a limited effect on reducing heat-related discomfort in operative staff, while simultaneously aggravating cold-related discomfort in anesthesiologists. This finding is particularly relevant in ORs, where airflow velocity is primarily adjusted for contamination control rather than thermal comfort.

### *3.4. Influence of Air Temperature on Thermal Comfort*

Figure 4 illustrates the effect of air temperature on thermal dissatisfaction (PPD). Under typical OR temperature ranges (19–22 °C) defined by standards and clinical practice, low dissatisfaction (PPD < 10%) was observed only for male anesthesiologists wearing lead aprons and for female surgeons and technical assistants without lead aprons [13]. All other staff constellations exhibited thermal dissatisfaction. Female surgeons wearing lead aprons would require approximately 16 °C to reach thermal comfort (PPD < 10%). In contrast, even at 16 °C, 48% of male surgeons wearing lead aprons remained dissatisfied due to perceived heat stress.

In anesthesiologists without lead aprons, discomfort was mainly cold-related in women and heat-related in men: at 26 °C, 19% of women still felt too cool, whereas 14% of men reported heat-related dissatisfaction. In contrast to surgeons and technical assistants, whose discomfort was mainly driven by heat stress, thermal comfort in anesthesiologists improved consistently with increasing clothing insulation. The use of lead aprons markedly reduced cold-related dissatisfaction in both sexes, primarily due to the increased thermal insulation (0.49 Icl without vs. 0.93 Icl with a lead apron).

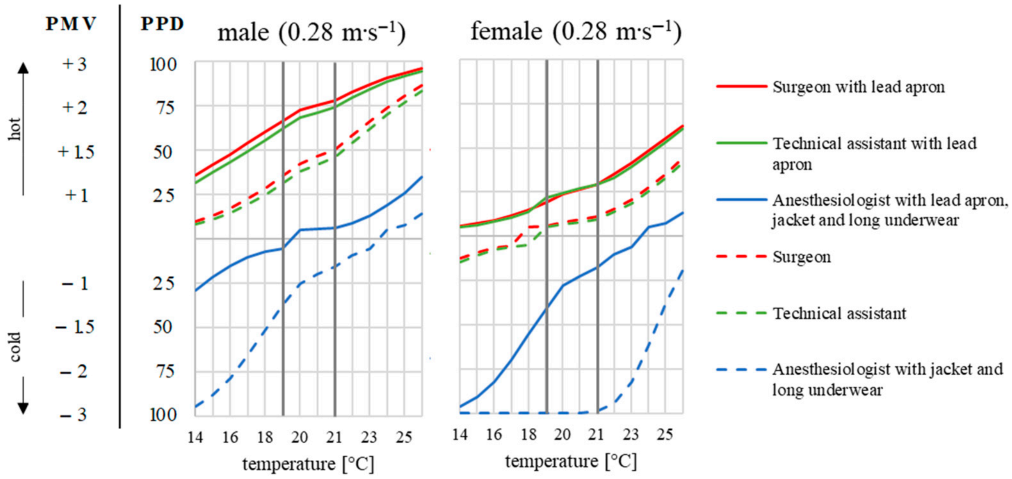


**Figure 4.** Percentage of thermally dissatisfied staff (PPD, 0–100%) as a function of air temperature for male and female operating room personnel with a pre-obese body mass index. Results are stratified by professional group (surgeons, sterile-dressed technical assistants, and anesthesiologists) and by absence or presence of lead aprons (7.5 kg). Calculations were performed at a constant air velocity of 0.28 m·s$^{-1}$. Decreasing air temperature reduced heat-related dissatisfaction among surgical staff but simultaneously increased cold-related dissatisfaction among anesthesiologists, illustrating the opposing thermal demands between professional groups. Vertical lines at 19 °C and 22 °C indicate the lower and upper bounds of commonly applied operating-room temperature ranges in clinical practice. PPD values are shown as absolute positive percentages. Graphical positioning above or below the x-axis is used solely to indicate the direction of PMV-derived thermal sensation (heat-related vs. cold-related discomfort) and does not represent negative PPD values.

### *3.5. Influence of Lead Aprons on Thermal Comfort*

The weight of lead aprons affected thermal comfort in surgeons and technical assistants due to their working in a forward-bent posture. At an air temperature of 20.5 °C, male surgeons with 7.5 kg lead aprons showed pronounced heat-related dissatisfaction (PPD 75%). At 19 °C, dissatisfaction decreased to PPD 66% (female surgeons: PPD 26% at 20.5 °C, PPD 19% at 19 °C, respectively).

At 19 °C, dissatisfaction in male surgeons increased with apron weight, ranging from 32% PPD (3 kg) to 66% PPD (7.5 kg) and 93% PPD (13 kg), indicating a strong dose–response relationship between apron weight and heat-related discomfort.

### *3.6. Influence of Body Mass Index on Thermal Comfort*

In surgeons of both sexes, increasing BMI was associated with improved thermal comfort, reflected by decreasing heat-related dissatisfaction. For example, under identical environmental conditions, PPD decreased from 66% in pre-obese surgeons to 51% in those classified as obese class I (female surgeons: PPD 19% vs. 13%). The highest heat-related dissatisfaction occurred in surgeons with normal BMI wearing heavy lead aprons, indicating a combined effect of a reduced surface area for heat dissipation and the additional static muscular effort required to counteract the external load.

In contrast, BMI showed an inverse effect in anesthesiologists. Female Anesthesiologists were predominantly affected by cold-related discomfort, which reached PPD 99% in women with normal BMI and PPD 100% in those with obese class I, while male anesthesiologists also reported increased cold discomfort (PPD 23% vs. 59% for normal body weight vs. obese class I).

Wearing lead aprons improved thermal comfort in anesthesiologists by providing additional insulation. Females with normal BMI wearing 7.5 kg lead aprons showed low cold-related dissatisfaction (PPD 14%); however, dissatisfaction increased to PPD 63% with increasing BMI, indicating that higher body mass reduced the beneficial insulating effect.

## 4. Discussion

This study reveals pronounced differences in thermal comfort between professional groups and genders in ORs. These differences arise from physiological characteristics, activity levels, and the protective clothing worn by the OR team. As they vary considerably, they cannot be fully resolved by heating, ventilation, and air conditioning (HVAC)-related conditions alone under the investigated settings. The observed divergence in thermal perception between professional groups is consistent with findings from previous field-based studies in operating rooms, which have repeatedly reported cold-related discomfort among anesthesiology staff and heat-related strain among surgical personnel. Similar role-dependent differences in thermal perception have also been reported in broader hospital environments, where varying activity levels and clothing insulation lead to heterogeneous comfort requirements among occupants [30]. While these patterns have been consistently described in observational and survey-based studies, the present analysis extends existing knowledge by providing a structured, quantitative assessment of the relative contribution of key influencing factors under standardized conditions.

Under clinically realistic conditions (20.5 °C, 0.28 $m \cdot s^{-1}$, sterile clothing, 7.5 kg lead apron, and pre-obese BMI), male surgeons experienced pronounced heat-related discomfort, whereas female surgeons were less affected. This finding is consistent with the up to 40% higher muscle mass and lower body fat percentage in men reported in physiological studies [31–33], resulting in a 5–25% higher metabolic heat production.

In contrast, anesthesiologists exhibited the opposite response under identical environmental conditions. Females predominantly experienced cold-related discomfort, while males reported lower levels of dissatisfaction. Without the insulating effect of lead aprons, cold discomfort among female anesthesiologists increased to near-complete dissatisfaction. These results demonstrate that identical HVAC conditions can induce opposing thermal strain within the same OR. This finding is in line with previous field observations but additionally allows an estimation of the magnitude of this discrepancy and its dependence on modifiable and non-modifiable parameters. Comparable contrasts in thermal perception between occupants with different activity levels have also been described in hospital environments, where low-activity staff are more prone to cold discomfort, while physically active personnel tend to experience heat-related strain under identical ambient conditions [30].

From an occupational health perspective, these differences imply distinct risks: heat stress in surgeons and technical assistants and cold stress in anesthesiologists. Both conditions may impair performance and safety and therefore require targeted mitigation strategies rather than uniform environmental control.

Although differences were observed between surgeons and technical assistants, these differences were quantitatively small (PPD $\leq$ 2–5%). Both groups share similar activity profiles, postures, and mandatory protective clothing. Surgeons showed slightly higher heat strain, likely due to prolonged forward-bent posture and increased static muscular effort. Given the magnitude of the contrast between operative staff and anesthesiologists, our data suggest that surgeons and technical assistants may be considered as a single group for thermal comfort evaluation.

### 4.1. Influence of Air Velocity

Air velocity is a critical parameter for contaminant control in ORs, particularly for the removal of surgical smoke, anesthetic gases, and airborne pathogens. UDF systems with velocities of 0.23–0.35 $m \cdot s^{-1}$ enable rapid displacement of contaminants from the protected zone. It is therefore important to note that air velocity, while crucial for air quality, has only a limited influence on thermal comfort. Even under clinically relevant variations in airflow, changes in thermal dissatisfaction remained small (approximately 4–8% PPD), indicating a limited capacity of air velocity to compensate for thermal strain. This limited cooling effect is consistent with the PMV–PPD framework according to ISO 7730, in which air velocity has only a secondary influence on thermal sensation compared with air temperature and metabolic rate, particularly under moderate indoor conditions [22].

Measurements under normative test conditions and intraoperative scenarios with surgical lights and monitors showed no relevant differences in air velocity within the protected zone, indicating a negligible influence of these configurations on thermal comfort. Overall, increasing air velocity is effective for contaminant control but appears unsuitable as a primary measure to balance thermal comfort among OR staff. This helps to clarify a common assumption in clinical practice, where high airflow is often perceived as the main driver of cold discomfort, particularly among anesthesiology staff.

Importantly, while the general relationships between environmental parameters and thermal comfort are inherent to the PMV–PPD model, the present results provide a context-specific interpretation for ORs. In particular, they quantify the magnitude of this effect under realistic OR conditions and demonstrate that airflow-related cooling remains insufficient to offset heat strain in highly insulated and metabolically active staff. In particular, the data indicate that air velocity has only a limited effect on thermal comfort and does not explain the pronounced cold-related discomfort reported by anesthesiologists, which is often attributed to high airflow in clinical practice. In contrast, even small changes in air temperature resulted in substantial and opposing effects between professional groups.

### *4.2. Role of Air Temperature*

Among all investigated HVAC parameters, air temperature exerted the strongest influence on thermal comfort. Small temperature changes resulted in marked changes in PPD across all professional groups and both sexes. This dominant role of air temperature is consistent with the PMV–PPD model, in which air temperature is one of the primary determinants of thermal sensation, with a stronger impact than air velocity under typical indoor conditions [22]. However, the direction of these changes was opposing: surgeons frequently perceived conditions as too warm, while anesthesiologists simultaneously perceived them as too cool ($p < 0.001$). Similar conflicts between different occupant groups have been reported in hospital environments, where activity level and clothing insulation lead to diverging thermal requirements under identical ambient conditions [30]. However, the present results allow a more detailed differentiation of these effects by quantifying their magnitude across professional groups and individual characteristics.

Adjusting the air temperature alone does not appear sufficient to resolve this conflict. Lower temperatures reduce heat-related strain in surgeons but cause pronounced cold discomfort in anesthesiologists, whereas higher temperatures exacerbate heat strain and sweating in surgeons, potentially increasing infection risks [10–12]. Moreover, the permissible temperature range in ORs (19–26 °C) appears insufficient to accommodate both groups simultaneously under the investigated conditions. This limitation is reflected in existing standards and guidelines, which define acceptable temperature ranges but do not account for the markedly different thermal demands of heterogeneous user groups within the same space [2,13,17].

### *4.3. BMI and Lead Apron Weight*

BMI significantly influenced thermal comfort, as an increase in BMI is associated with a larger body surface area and thus greater heat loss. In addition, body composition associated with higher BMI, including increased subcutaneous fat, alters heat storage and dissipation, thereby influencing thermal perception [31,32]. In surgeons, a higher BMI was associated with improved thermal comfort, whereas in anesthesiologists, it showed the opposite effect. Thermal dissatisfaction in normal-weight male surgeons decreased from PPD 80% to 51% in obesity class 1, even when wearing heavy lead aprons. In anesthesiologists, the same increase in body surface area intensified cold discomfort, particularly in women. With lead aprons, cold-related dissatisfaction increased markedly with increasing BMI, whereas without lead aprons, it remained close to complete dissatisfaction across all BMI categories. This opposing effect reflects the interaction between metabolic heat production, insulation, and activity level, which differs substantially between active and predominantly sedentary staff [30]. To the best of our knowledge, this is the first study to explicitly integrate the combined effects of lead apron weight, metabolic rate, and clothing insulation into a unified thermal comfort analysis for OR staff.

BMI also indirectly affected thermal strain due to the size and weight of the lead apron. Larger apron sizes required for higher BMI can increase the static weight load by more than 40% and thus contribute to additional heat-related strain without improving radiation protection. The additional weight and impermeability of lead aprons further reduce convective and evaporative heat loss, thereby exacerbating heat strain under physically demanding conditions. This highlights the importance of BMI-adapted selection of protective equipment.

Comparable findings regarding clothing insulation in surgical environments have been reported in previous studies. Zwolińska and Bogdan [34] determined clothing insulation values between 0.99 and 1.49 Icl for different types of surgical garments under controlled climatic conditions. These values are higher than the mean insulation of 0.89 Icl calculated in our study, which may be explained by differences in experimental conditions, particularly lower air velocities (0.1 m·s$^{-1}$) and higher ambient temperatures (24 °C) used in their climate chamber experiments. In addition, the inclusion of lead aprons, which significantly affect thermal insulation and heat dissipation, was not clearly specified in that study. Similarly, Samadi et al. [35] reported clothing insulation values of approximately 0.86 Icl in a CFD-based analysis of ORs with UDF systems, which is in close agreement with our results. Their simulations also confirmed that airflow velocities in the range of 0.20–0.35 m·s$^{-1}$ have only a limited impact on thermal comfort, supporting our findings under real measurement conditions. Taken together, these comparisons highlight that differences in environmental boundary conditions, airflow regimes, and protective equipment substantially influence thermal comfort assessments and must be carefully considered when transferring results between experimental and clinical settings.

### *4.4. Implications for HVAC Design and Mitigation Strategies*

The present results indicate that conventional environmental control strategies are insufficient to balance thermal comfort between professional groups. This finding is consistent with previous research in hospital environments, which demonstrates that thermal comfort requirements vary substantially between occupants depending on activity level, clothing, and physiological characteristics [30]. Instead, the identified opposing thermal demands suggest the need for role-specific mitigation approaches, which should be evaluated in future studies using objective physiological and environmental measurements. In this context, the present model-based approach can serve as a framework to systematically identify relevant parameters and guide the design of future field-based investigations.

The pronounced and opposing effects of profession, sex, BMI, and protective equipment indicate that a single "optimal" thermal environment for all OR staff is unlikely to be achievable. This is in line with current standards (e.g., ISO 7730, E), which define ranges and categories of thermal comfort rather than a single optimal condition. Consequently, calculating an average thermal comfort value for the entire OR team appears neither meaningful nor practical.

Temperature adjustments alone are unlikely to compensate for these differences. While clothing-based insulation and localized heating (e.g., heated seating) can effectively mitigate cold discomfort in anesthesiologists, operative staff have very limited compensatory options. Similar conclusions have been reported in studies on surgical staff, where increased clothing insulation or localized heating improved comfort for sedentary personnel but did not adequately address heat strain in active staff [17,19]. Neither their physical activity level nor their protective clothing is modifiable under routine clinical conditions, and further reduction in room temperature may be constrained by patient safety requirements.

Therefore, there is a need for the development of lightweight, effective active cooling garments for surgeons and technical assistants. Personal cooling systems have been proposed in occupational settings with high thermal loads and limited environmental control, showing potential to reduce heat strain without compromising ambient conditions [4,6]. Convective air-perfused cooling systems appear promising, whereas passive cooling systems with phase-change materials may be of limited practicality due to weight and short duration.

### *4.5. Limitations*

Several OR-specific heat sources are not fully represented by PMV–PPD calculations according to ISO 7730 [22]. These include radiant heat from dynamically positioned surgical lights, additive heat transfer through direct contact with patients and warming devices, warm exhaust air from medical equipment, and additional insulation from sterile drapes, which impede heat dissipation through protective clothing. As a result, local and transient heat-related strain in surgeons may be underestimated.

The approximation of mean radiant temperature may lead to an underestimation of radiant heat exposure, particularly for surgical staff exposed to localized radiation from surgical lights. Furthermore, the radiative environment in ORs is highly dynamic due to frequent repositioning of surgical lights and spatially heterogeneous exposure, which limits the feasibility of standardized measurement approaches. Accordingly, mean radiant temperature was not directly measured in the present study and should therefore be regarded as a methodological limitation of this comparative screening approach.

Variations in relative humidity were not explicitly considered, which may influence thermal perception under certain conditions.

The absence of surgical staff during measurements may limit the direct transferability of the results to real intraoperative conditions. Although the environmental parameters were assessed under standardized and reproducible conditions, the presence of staff may alter airflow patterns and local heat exchange, which is not fully captured in the present study.

The interaction between air movement and clothing's thermophysical properties was not explicitly modeled. This simplification may affect the accuracy of thermal comfort predictions, particularly under conditions with variable airflow and multilayer protective clothing. More advanced correction approaches accounting for the combined effects of air velocity, clothing insulation, and thermophysical clothing properties are described in Annex C.2 of ISO 7730:2025 and have also been discussed in previous studies addressing heat-strain prediction models under protective clothing conditions but were beyond the scope of the present comparative screening study [22,36].

In addition, the assessment was intentionally limited to comfort-based indices (PMV–PPD) to enable a comparative and clinically interpretable evaluation of thermal conditions between professional groups. According to ISO 15265, elevated PMV values may indicate a transition from thermal discomfort to physiologically relevant heat stress conditions, requiring a shift from comfort-based assessment approaches toward stress-based evaluation models such as the Predicted Heat Strain model, according to ISO 7933 [37,38]. This transition between thermal discomfort and heat stress has been discussed in detail by d'Ambrosio Alfano et al., who emphasized that PMV-based comfort indices may become insufficient under conditions associated with substantial thermal load and elevated metabolic demand [39]. In the present study, such an extended heat-stress-oriented risk assessment was intentionally not performed because the objective was limited to a standardized comparative screening analysis of thermal comfort differences between professional groups under defined OR conditions rather than an occupational exposure-limit assessment. Accordingly, the present results should be interpreted as a comparative assessment of thermal comfort rather than a comprehensive heat stress risk evaluation.

The analysis further assumes a spatially uniform thermal environment, which represents a simplification of real OR conditions. In practice, thermal exposure may differ substantially between locations and roles, particularly between anesthesiologists and surgeons exposed to localized radiant heat sources.

Metabolic rate was estimated based on standardized reference values according to ISO 8996 and related norms rather than direct physiological measurements. While this approach enables comparability and reproducibility, it may not fully reflect interindividual variability and dynamic workload changes during surgical procedures.

Overall, the presented results should therefore be interpreted as model-based screening approximations under defined boundary conditions, providing a structured comparison of thermal influences rather than an exact representation of individual thermal perception or physiological heat strain under real clinical conditions. Future studies should integrate physiological and subjective assessments under real intraoperative conditions and include more comprehensive microclimatic measurements (e.g., mean radiant temperature and relative humidity) as well as risk-based modeling approaches. Such studies would also enable a direct validation of the model-based assumptions presented here.

## 5. Conclusions

Thermal comfort in ORs is strongly influenced by professional role, sex, activity, BMI, protective clothing, and air temperature. Under representative conditions (20.5 °C, 0.28 $m \cdot s^{-1}$, and pre-obese BMI), up to 75% of male surgeons wearing lead aprons were classified as thermally dissatisfied due to heat-related strain, whereas up to 22% of female anesthesiologists experienced cold-related strain under the same HVAC conditions.

Air velocity, while essential for contaminant control, has only a limited effect on thermal comfort, with variations in airflow resulting in only minor changes in PMV and PPD values. Air temperature is an important parameter, but it does not appear sufficient to satisfy all professional groups simultaneously within normative limits.

BMI modifies thermal comfort in opposite directions for surgical staff and anesthesiology; for example, thermal dissatisfaction in male surgeons decreased from approximately 80% to 51% with increasing BMI, and additionally affects thermal load through lead apron size and weight. These findings suggest that a uniform thermal environment for the entire OR team is unlikely to be achievable.

Effective mitigation therefore requires differentiated, role-specific strategies, as environmental control alone cannot resolve the opposing thermal demands identified in this study. These may include effective insulating clothing for anesthesiologists and the development of active cooling solutions for surgeons and technical assistants. The quantitative findings of the present study provide a basis for future investigations to objectively evaluate such interventions under real clinical conditions.

**Author Contributions:** Conceptualization, H.-M.S.; methodology, H.-M.S. and M.Z.; validation, T.S., M.Z. and J.H.-N.; formal analysis, M.Z. and J.H.-N.; resources, H.-M.S.; data curation, M.K. and M.Z.; writing—original draft preparation, J.H.-N. and M.Z.; writing—review and editing, M.K., H.-M.S. and T.S.; visualization, M.Z. and M.K.; supervision, T.S.; project administration, H.-M.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are contained within the article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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