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Thermal Environment Perceptions from a Longitudinal Study of Indoor Temperature Profiles in Inpatient Wards

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Abstract: Inpatient wards in general have cooling systems with a "one-size-fits-all" approach, driven by a fixed set-point temperature (21–24 °C) that is flexible to lower limits down to 18 °C or less. This approach does not consider patients' temperature demands, which vary due to thermo-physiology caused by medical conditions, and mixed demographics. It also causes additional cooling demands in hot climates that are infrequently utilized by patients, who tend to adopt warmer internal set temperatures. Thus, this research examined the indoor temperature profiles (distribution of shape) in patient rooms in fully air-conditioned inpatient wards over an extended period of time. During four months of summer, longitudinal monitoring of internal temperature and relative humidity was carried out in 18 patient rooms in the surgical, medical, cardiology, and oncology wards of two hospitals in Saudi Arabia. In parallel, 522 patients were surveyed to capture common subjective thermal indices. The findings revealed that the most frequently preferred temperature (peaks) varied significantly between wards; peaks (modes) were 20.1–21.8 °C in cardiology; 22.2–23.9 °C in the surgical ward; warmer 24.8–25.3 °C in medical ward; and 25.3–26.8 °C in oncology. Surveys also showed that patients were not satisfied with the indoor environment in both hospitals. Given the significant variance in temperature profiles between wards and patient dissatisfaction with the indoor environment, these results suggest that more appropriately designed zoned cooling strategies are needed in hospitals as per the nature of each ward. Besides its implications for benchmarking the HVAC system, this approach will substantially reduce energy loads and operational costs in hot-climate hospitals if patients desire warmer conditions than the set conditions provided by system.

Keywords: longitudinal study; indoor temperature profile; set-point range; thermal environment; cooling strategy

1. Introduction

Hospital environments are one of the most complex spaces due to different requirements from patients and other users, which mostly involve functionality or quality of care [1]. While complying with hospital guidelines is generally not difficult, certain challenges may arise when applying these to a proper design process [2]. Such challenges are evident in patient rooms, a critical space occupied by patients for short/extended periods, wherein they receive medical care throughout their treatment and recovery journeys, and which need to be regulated together with other operational and safety requirements of practice codes and standards. The modern environmental designs of inpatient rooms enable patients to control/adjust their indoor temperatures to the desired levels considering their personal medical conditions and activity levels. Such thermal control gives patients a greater sense of belonging to the space that they are hospitalized in. Hence, operational system requirements may interfere with patient thermal comfort demands. This can be addressed by striking a balance between different characteristics of patients and staff members [3]. Another issue regarding patient room design is that various stakeholders, such as nurses, doctors, and visitors, carry out different occupational activities inside these rooms [4].

In hospitals, the role of heating, ventilation, and air conditioning (HVAC) is to maintain thermal comfort parameters within the patients' comfort zones through the control of indoor temperature, relative humidity, air distribution, and odours [5]. In terms of thermal satisfaction, it is known that different users within the same hospital zones have varying thermal environment demands due to their variety of medical conditions, activity levels, and clothing types (pull-gowns), in addition to other factors, such as age and length of stay in the ward. Thus, arrangements must be made to maintain the satisfaction of the majority of users [6]. Lavender et al. reported that giving patients control over their room temperature from the comfort of their beds is one of many design interventions [2]; this has been shown to improve patients' thermal comfort and lower incidents of falling, as patients do not need to get out of their beds to adjust the thermostat. Furthermore, Carpenter stated that new room designs have implemented individual control of room temperature alongside other design features, such as social spaces for families, patient entertainment, and access to wireless facilities [7].

In order to accommodate the different requirements of heating and cooling strategies per group of users in hospitals, an intelligent HVAC system for the hospital environment is needed to reflect those requirements. It is defined by [8] as the process of designing a HVAC system that is capable of accounting for different aspects, such as indoor climate, energy saving, and variety of facility types, to enhance the working atmosphere and productivity and reduce indoor air symptoms [8–10]. Prior to that, thermal comfort is a vital aspect to consider before planning of any design intervention because an intelligent HVAC system must maintain the thermal environment for different users. Thus, this study focused how hospitalized patients perceive their indoor environment during recovery periods.

1.1. Thermal Comfort in Hospitals

Methodological approaches regarding thermal comfort often simultaneously record the indoor environmental variables for a short period of time alongside occupant surveys [11] and have been applied in many studies, such as [12–15]. The most commonly-used indicator is the predicted mean vote (PMV), with preference scales between (−3) and (+3). The PMV was devised by Fanger in the early 1970s [16], but has many limitations in application—especially in sensitive environments such as hospitals—because it was not originally devised for non-healthy populations. Thus, the assessment of thermal comfort for different hospital staff and patients has encountered several issues, particularly when the PMV model is used for patients with a range of acute medical conditions, low activity rates, and reduced clothing levels. The thermal preference vote (TPV) is also widely-used for recording occupant preferences of their indoor environment based on a 7-point Likert scale devised by Bedford [17], where (4) is the comfortable point. As proposed by ISO 7730-2005 [18] and ASHRAE-55 [19], an indoor environment is considered comfortable when 80% of PMVs fall between (−0.5 and +0.5) and 80% of thermal sensation votes (TSV) lie between (−1 and +1). The PMV either overestimated or underestimated TSV in the majority of studies in hospitals, such as [20–23]; however, [24] showed no difference between the PMV and the TSV. The PMV model purports to independently predict the neutral (comfort) temperature with no consideration for the external temperature [25].

The problem with thermal comfort analysis in hospitals lies in considering the variety of requirements among different users, especially those using the same spaces (i.e., nurses have increased activity levels in nursing wards compared to inpatients who lay on their beds most of the time). These differences create issues when devising cooling or heating systems in terms of cost and thermal satisfaction for each user group. For example, patients often prefer warmer temperatures than nurses, but heating/cooling systems must ensure that these warm temperatures do not violate any safety and ventilation requirements. Therefore, compromises are required to maintain the minimum levels of thermal comfort in patient rooms and satisfy all users. Explicit evidence was found in the literature about differences in thermal perceptions between patients and staff; a study in a Swedish hospital done to distinguish between the thermal environment perceptions of patients and staff reported that neither patients nor the staff perceived the indoor air temperature to be acceptable, especially during the winter [26]. Additionally, Del Ferraro et al. stated that patients and staff must be considered as two groups with different thermal needs and that the PMV rarely described patient requirements in Italian hospitals adequately [20].

1.2. Research Objectives

This work extends previous research [23] that evaluated the suitability of thermal comfort approaches and standards for inpatients in air-conditioned hospitals. Wide ranges of indoor temperature were experienced by inpatients with no clues as to how these ranges could be interpreted among patient groups or specialized wards. Thus, this research aimed to evaluate perceived indoor temperature profiles over an extended period of time for patient rooms (single and double occupancy beds) with more long-term occupancies of up to (4-months). With the analyzed temperature profiles, we sought to determine how effective the existing cooling strategies already applied in inpatient wards are. The objectives of this research are shown in Table 1.

Table 1. Research objectives, approaches, and methods (methods are detailed in Section 2).

Objective	Approach	Method
(1) To determine whether indoor temperature profiles reveal significant peaks either in each patient room or a particular ward over an extended period of time.	Random selection of regular patient rooms (single and double bed) in different inpatient wards proceed to elucidate how these profiles, comply with fixed set-point design temperature driven by practice codes.	Monitoring temperature and relative humidity of separately in each room for four months alongside measuring air velocity on several occasions.
(2) To investigate if such peak profiles are influenced by increase/decrease at particular times of the day and relative humidity levels.	Determine the relationship between temperature and humidity in each room if any increase/decrease has meaningful trend.	Fitting mixed effects model and considering 'room' as random variable.
(3) To propose revised a set-point temperature that reflects patient thermal demands per room or ward if applicable.	Identify temperature ranges in all rooms and classify per ward type if similar peaks found.	Detecting the peaks (modes) of temperature in term of bimodal distribution and the degree of skewness if rooms tend to cold or hot based on statistical analysis.
(4) To determine subjectively if patients are thermally comfortable with the indoor environment.	Capture patients' perceptions of thermal environment during hospitalization by common indices.	Collating TSV and TPV votes for all surveyed patients. ordinal scale for sensation and preferences.

2. Methodology

This study was undertaken from June to September 2018 at two hospitals: the King Abdullah Medical City (KAMC), a public specialist hospital in Makkah, and the International Medical Centre (IMC), a state-of-the-art private hospital in Jeddah. Both hospitals are located in the Western province of Saudi Arabia. The hospitals were targeted due to their different wards and occupancy types (single vs. double); KAMC has two specialist wards (cardiology and oncology), while IMC has two general wards (surgical and medical). The surgical and medical wards at IMC accommodate patients with different medical conditions, including orthopaedic, neurological, gastroenterological diseases, etc., whereas the cardiology and oncology wards at KAMC specialize in critical stages of related diseases, including cancer treatment and heart surgeries. This distinction enabled the research to examine several types of inpatient environments with a variety of medical conditions and demographics (Table 2). Isolation rooms and ICU units were beyond the scope of this research, as they have specific requirements for ventilation and indoor air quality (IAQ), such as relative humidity, pressurization (positive or negative), air filtration, air changes per hour (ACH), etc. The following methodologies were applied as they are widely used in studying thermal comfort in hospitals, [27–30]:

1. Longitudinal monitoring of indoor air temperature (T_a °C) and relative humidity (Rh%).
2. Administration of patient surveys with selected questions about thermal comfort perceptions and health indicator information.

Table 2. Reference hospitals' profiles.

	IMC	KAMC
Opened year	2006	2011
Total area	10491 m^2	25812 m^2
No. of floors	6	5
Capacity (beds)	300	527
Occupancy	Single bed	Double bed
Funding	Private	Public
Mechanical system	Centralized HVAC system air handling unit	
Selected wards	Surgical Medical	Cardiology Oncology
Measured rooms	8	10

2.1. External Climate

Jeddah and Makkah share climatic characteristics—both have a typically hot, arid dessert climate (BWh on the Köppen Geiger climate zones map) [31]. In Jeddah, the annual mean temperature is 28.85 °C; the maximum and minimum temperatures are 34.57 °C and 23.13 °C. The highest maximum temperature (52 °C) is observed in June, while the lowest minimum temperature (25 °C) is observed in February, and June through August is the summer season in this city. The relative humidity is an average of 62.8% and ranges from 57% (July) to 73% (January). In Makkah, the mean annual temperature in 2018 was 31.9 °C; the mean maximum and minimum temperatures were 38.6 °C and 25 °C between June and August 2018. The average external humidity was 46% and ranged from 34% (June) to 60% (December) in the same year. It is worth noting that Makkah and Jeddah have no heating degree days (HDD), but Makkah records the upper annual mean cooling degree days (CDD) of 7549 [32]. All the climatic information during the data collection were accessed through the Department of Meteorology, King Abdul-Aziz University (KAU) in Jeddah, Saudi Arabia in 2018 (Figure 1).

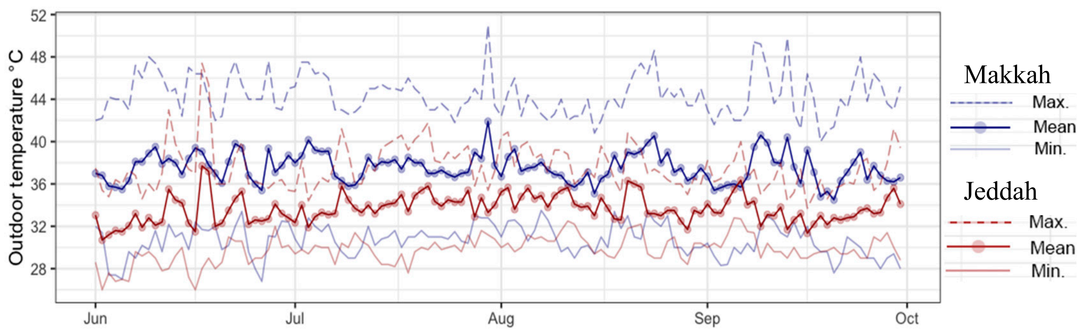

Figure 1. Daily (maximum, minimum, and mean) outdoor temperatures for Jeddah and Makkah in 2018.

2.2. Sampling Method

Both transverse and longitudinal sampling are used commonly in thermal comfort fieldwork. The transverse method uses a large number of subjects to eliminate possible biases that could be encountered with a small dataset and to increase the statistical significance of the dataset [33]. However, the main issue associated with the transverse method, particularly in hospitals, is that inpatients' perceptions of their indoor thermal environment are affected by their experiences with several underlying conditions, such as the progressing nature of their illnesses at different medical or recovery stages, and the impacts of certain medications (related to thermo-physiology). To avoid this concern, this study used longitudinal sampling to track the patients' behavior (in terms of selected indoor environment variables) during their stay. This method, as used by [34–37], allows the researcher to track environmental details, changes in a single person or group of people, and their perceptions over a long period of time, in this case 4 months [33].

2.3. Data Collection

A total of 522 inpatients agreed to participate in this study by completing surveys. Table 3 illustrates the demographic mix of patients involved in the study. The IMC Research Centre and Institutional Review Board (IRB) at KAMC approved the execution of this research during the selected period. Each patient provided their informed consent prior to answering the survey. All surveys were distributed during non-visiting hours (between 12:00 and 16:00) to ensure that the patients would not be disrupted while completing or inquiring about some questions in the survey.

The survey was designed to gather information about thermal comfort in patient rooms based on different common indices and scales according to ASHRAE-55 and ISO 7730:2005. The scales were based on a 7-point ordinal TSV (−3 to +3) and TPV (1 to 7). It likewise included several questions about health conditions, such as nature of their health conditions, length of stay, and frequency of hospital admission over the last five years. In Figure 2, the length of stay is divided into 5 bands; (1) first day, (2) 2–3 days, (3) 4–6 days, (4) more than one week, (5) more than month, and admission to hospital with the choice to select from 1–5 hospital stays. It was originally developed in English and then translated into Arabic—the spoken language of the majority of patients. The surveys were first given to the patients for them to answer the questions; in the event that they were unable to write, the patients were interviewed either by the researcher or their accompanying relative(s).

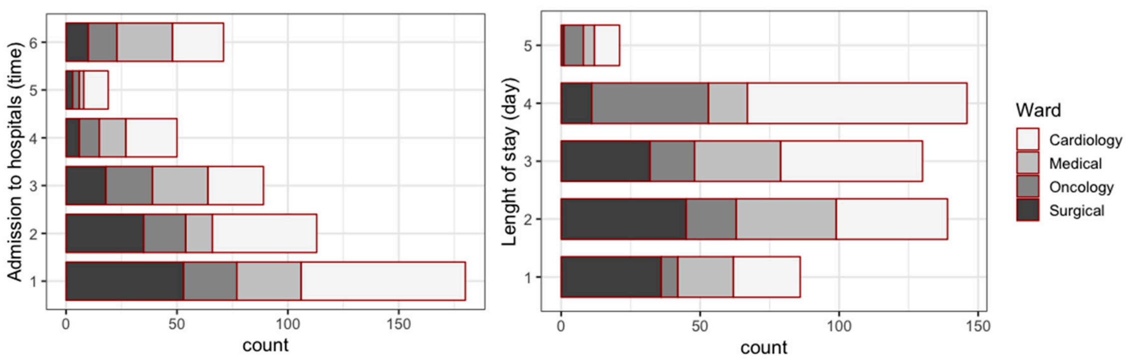

Figure 2. Patient health profiles classified per ward.

Table 3. Demographics of surveyed patients.

Hospital	Gender	Age Group							
		18–24	25–34	35–44	45–54	55–64	65–74	>75	Total
IMC	M	4	17	22	25	15	14	24	121
	F	9	17	26	16	20	13	8	109
KAMC	M	2	11	22	36	46	27	24	168
	F	4	9	15	24	30	28	14	124
Total		19	54	85	101	111	82	70	522

2.4. Measurements Protocol

Simultaneous longitudinal data of the indoor air temperature (T_a °C) and indoor relative humidity (Rh%) were recorded with air velocity (V_a) obtained by spot measurement on several occasions for four consecutive summer months (June, July, August, and September 2018) [38] (Supplementary Materials). Raspberry Pi +3 data-loggers (Table 4) were installed in 18 patient rooms in cardiology (5 rooms), oncology (5 rooms), surgical (4 rooms), and medical (4 rooms) wards (Figure 3). These data loggers were selected for being small, unobtrusive, economically viable, and with sufficient monitoring resolution. The following abbreviations are used to label wards in the analysis: surgical (SUR), medical (MED), cardiology (CARD), and oncology (ONCO). T_a and Rh were sampled at 5-minute intervals, and due to their similarity between readings, were subsequently averaged into a single 30-minute reading. In addition, although the air speed values in patient rooms were a low ≤0.2 m/s, due to restricted openable windows and well-controlled environments, they were still noted to include all thermal environment parameters. The air velocity was measured near to patient beds and at the patient's head height when the patient was lying on the bed. All measured rooms were occupied throughout the study period. Any vacant days or hours were checked with the assistance of the nurses and were extracted from the final dataset.

Table 4. Demographics of surveyed patients.

Sensor	Parameter	Accuracy	Range
Raspberry Pi sensor	Air temperature (DS18B20)	±0.5	−10 to +85 °C
	Relative humidity (RHT03)	±2%	0 to 100% RH
Thermal Anemometer	Air velocity	± (0.1 m/s + 5%)	0 to 30 m/s

The most common cooling strategies for hospitals in Saudi Arabia are air handling units (AUH) and fan coil units (FCO) depending on hospital size and different thermal zones. Calculated cooling loads for such strategies take into consideration key elements of the building envelope (i.e., well-insulated material, restricted openable windows, and internal and external shading). The hospitals were both fully air-conditioned with a central HVAC system that had low velocity type—group A, D, and E complied within Chapter 20 in the 2017 ASHRAE Handbook—Fundamentals [39]. The patient rooms in both hospitals were defined as regular patient rooms, having a single and double occupancy bed in IMC and KAMC, respectively. All rooms had well-controlled environments and provided a set-point of temperature between 21–24 °C and an upper limit of 60% Rh complying with ventilation requirements for healthcare facilities in ANSI/ASHRAE-170:2013 [40]. Each room had a separate thermostat that could adjust the room temperature at any time. Furthermore, the selected patient rooms had similar design features such as an identical layout, non-openable windows, and movable curtains.

Figure 3. Raspberry Pi +3 mounted in patient rooms in IMC (**left**) and KAMC (**right**).

2.5. Statistical Analysis

The analysis of T_a was undertaken using stepwise procedures to interpret the results. The T_a profiles for each patient room were individually inspected with kernel smoothing density to locate the temperature peaks (modes). The following steps were employed:

1. The normal distribution of aggregated T_a per ward was checked through a Shapiro–Wilk test (Figure 4) [41].
2. The T_a peaks were then detected using the excess mass method [42] to determine the number and positions of the different peaks (modes) in the dataset (i.e., multimodal, bimodal, and skewness direction).
3. A mixed-effects model was fitted to estimate the random variation caused by patient rooms due to the disparities in their demographics and severity of illness among the occupying patients.
4. ANOVA was used to compare the model baseline versions that determined the statistically significant differences.

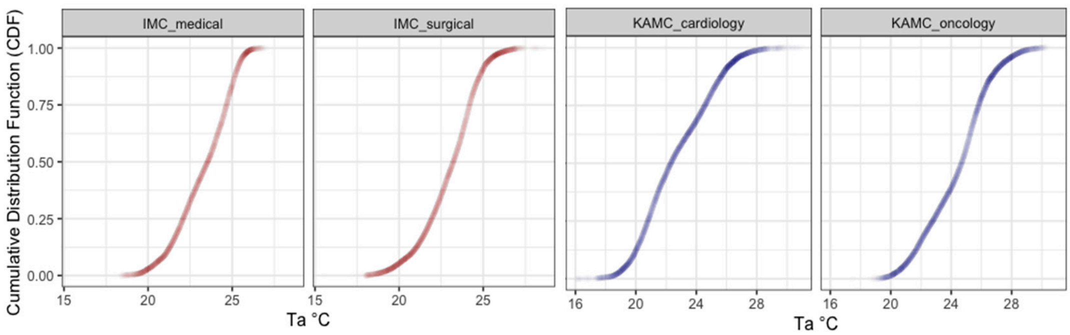

Figure 4. Estimator of Cumulative Distribution Function (CDF) plot showing the normal probability distribution of T_a per ward.

The thermal comfort surveys were analyzed in percentages and meaningful figures. All data were analyzed using R statistical-software [43,44]. Mixed effects model computed using the "lme4" package [45,46].

3. Results and Discussion

3.1. Thermal Comfort Survey

The inclusion of two hospitals was not for comparison purposes, as each hospital and patient group had different characteristics, and it looked at how robust the designs of their patient rooms were to thermal changes and patient requirements. Over 72% and 67% of TSVs between (−1 and +1) filled out by patients at IMC and KAMC, respectively, indicated that the indoor environments were not comfortable. These TSV findings were in line with 65% in three Malaysian hospitals [47], 70% in a Saudi private hospital [23], and 78.6% and 68.2% in two groups of patients in [48]. It is expected that those patients who voted out of the acceptable range (−1, 0, +1) did so to choose comfortable "4" on the TPV scale. Figure 5 shows that 71% and 70% of TPVs sought the thermal environment to be comfortable, and a smaller proportion, about 25% and 12%, indicated cooler conditions were preferred, while few only preferred warmer environments—3% and 17% at IMC and KAMC, respectively. Patients reported that the possibility of adapting the indoor environment was very limited because windows were unopenable, they had light clothing (pull-gowns), and there was an absence of dedicated spaces to walk if they were medically stable. A few strategies were available, such as using a blanket or extra sheet and walking inside the room.

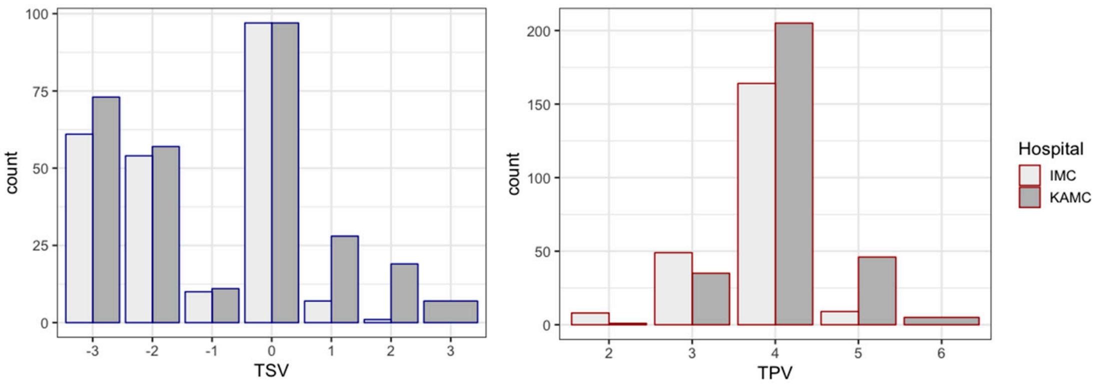

Figure 5. Distribution of thermal sensation votes (TSVs) and thermal preference votes (TPVs) in both hospitals.

3.2. Relative Humidity Ranges and Air Velocity

Thermal environmental conditions in patient rooms are associated somehow with indoor air quality (IAQ) parameters, as acceptable levels of indoor temperature and relative humidity are needed to prevent the growth of bacteria and the spread of viruses and infections [49–52]. The air velocity is an essential parameter, but was less than 0.1 m/s on average which was considered ignorable. Looking at Figure 6, all rooms were mostly in compliance with the acceptable limits of up to 60% humidity proposed by ASHRAE-170. Although there were minimal outliers detected across rooms (data points that were higher than 1.5 times the interquartile range), those outliers were located less than or equal to the 60% boundary. Thermostats mounted in rooms were only featured to adjust the room temperature, but with no such feature to control humidity levels. Some practice codes do not require monitoring of humidity levels because of its cost implications, such as HTM 03-01: Part A in the UK [53]. The average Rh% was similarly shown to be 39% in SUR, 36.5% in MED, 37% in CARD, and 35% in ONCO. Furthermore, Spearman's correlation was computed in each monitored room, revealing a negative moderate linear relationship between T_a and Rh (r = −0.5) in the majority of rooms based on size of correlation defined by [54]. This moderate relationship can be explained by HVAC systems that added air moisture irregularly to ducts before being streamed into patient rooms and not because of an increase or decrease in supply temperature.

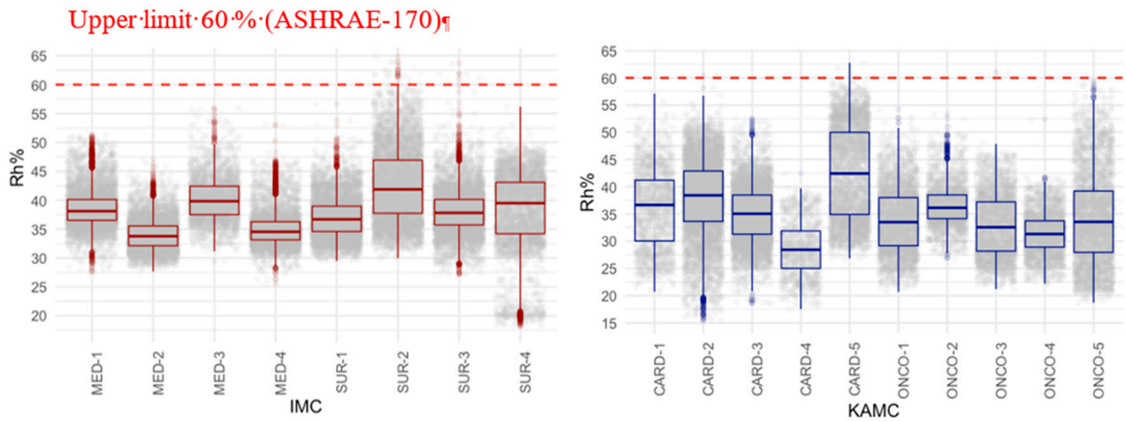

Figure 6. Relative humidity measurements for a four month period in both hospitals. The red dashed line refers to an upper acceptable limit of 60% proposed by ASHRAE-170. Note: room ID is just a random identification code and does not refer to room number.

3.3. Discrepancy of T_a in Occupied Patient Rooms

The concept of investigating patient rooms for long periods instead of each patient's stay emerged from the fact that the fluctuations in temperature for each patient are difficult to explain, as each patient experiences an extensive range of temperatures during his or her stay. Considering the discrepancy in T_a, it is unlikely that the patient rooms had a symmetrical T_a distribution, as this element is attributable to the underlying processes experienced during hospitalization. Hence, the selection of patient rooms was intended to shed light on indoor temperature profiles during a long period and to ascertain whether they were shaped based on regular patterns that can be further analyzed. According to Figures 7 and 8, the T_a in each room was not bell-curved, which indicated that the data were not derived from a normal distribution. Bimodal (two-peak distribution) and left-skewed data were visualized for all rooms in both hospitals. Considering the non-normal distribution of data, instead of the mean, the mode was chosen to show the most frequently preferred temperature.

3.3.1. IMC (Single-Occupancy Beds)

Notably, at the surgical ward in IMC, two temperature patterns were detected: left-skewed (two rooms) and bimodal (two rooms) (Figure 7). The mode in the left-skewed rooms was in a narrow range between 23.2 and 23.9 °C. This skewness reflected that the patients did not prefer temperatures lower than ~23 °C on most occasions. In the other ward, the medical patient rooms only demonstrated a bimodal pattern of temperature, indicating that two modes of temperature occurred. The first mode varied from 24.8 to 25.3 °C while the second mode referred to lesser temperatures from 20.5 to 22.5 °C. The T_a of the medical wards showed relatively consistent profiles, as the inpatients in this ward normally stayed longer than those in the surgical ward. Moreover, the patients had more severe medical conditions and interactions between diseases (e.g., as deduced from the survey on the patients' diagnoses/ailments, the elderly population suffered from simultaneous critical conditions). The average range (difference between the upper and lower temperatures) was 9 °C in both wards. Table 5 presents all of the modes recorded for four months that were associated with the descriptive statistics of the median and range.

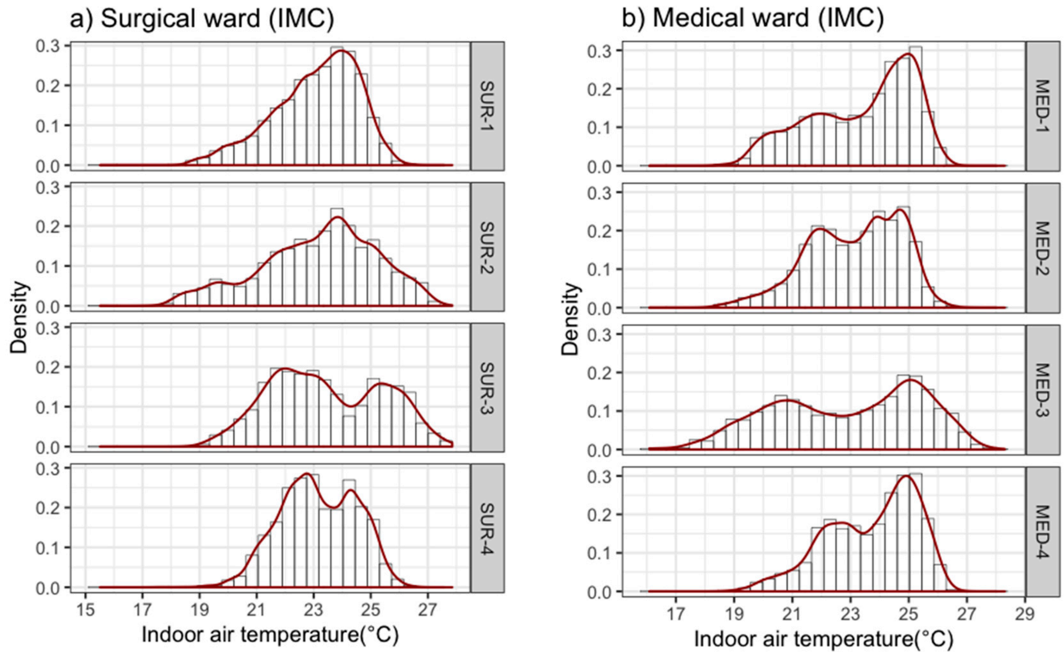

Figure 7. Distributions shapes of T_a at IMC. (red curve refers to kernel smoothing), (**a**) Surgical ward (IMC), (**b**) Medical ward (IMC).

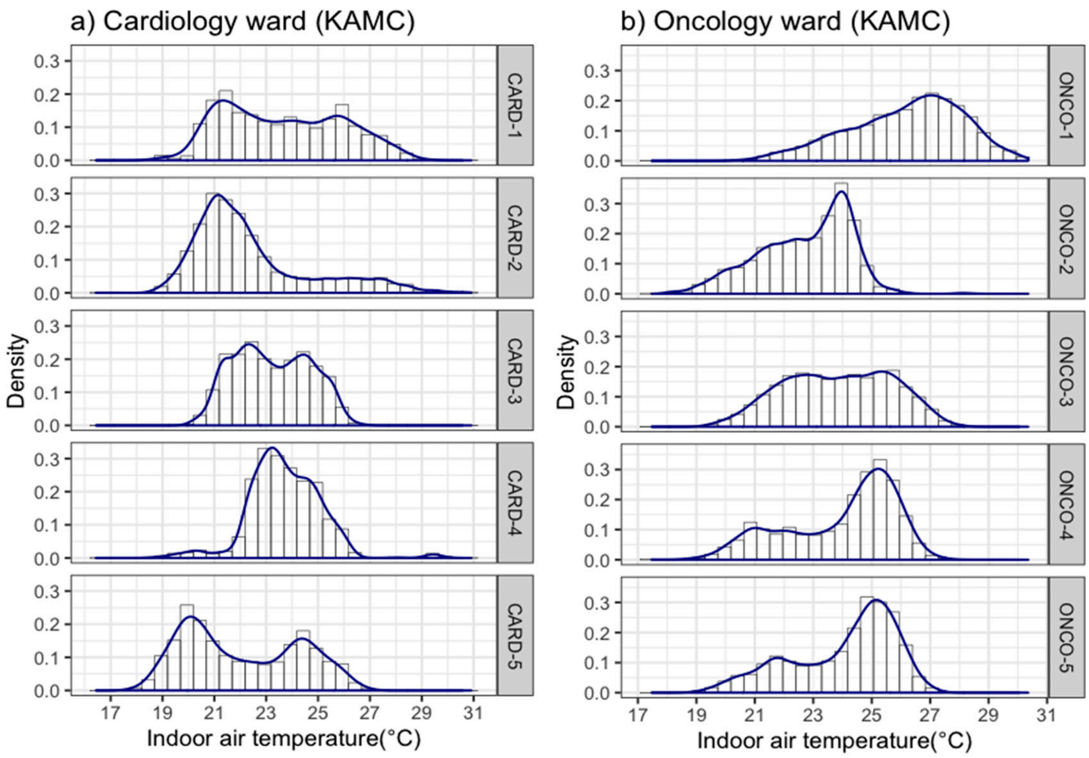

Figure 8. Distribution shapes of T_a at KAMC (blue curve refers to kernel smoothing), (**a**) Cardiology ward (KAMC), (**b**) Oncology ward (KAMC).

Table 5. Descriptive summary statistics of T_a in patient rooms in IMC and KAMC.

Room	T_a (°C)						Distribution Shape	r *
	Median	Min.	Max.	Range	Mode 1	Mode 2		
IMC								
SURG-1	23.30	18.26	26.44	8.18	23.2	—	Left-skewed	0.11
SURG-2	23.45	15.52	27.47	11.95	23.9	—	Left-skewed	−0.53
SURG-3	23.23	19.1	27.85	8.75	22.2	25.9	Bimodal	−0.17
SURG-4	23.06	17.66	26.47	8.81	22.9	24.3	Bimodal	−0.56
MED-1	23.87	18.56	26.38	7.82	25.2	21.7	Bimodal	−0.14
MED-2	23.34	18.01	27.01	9	24.8	21.9	Bimodal	−0.43
MED-3	23.24	16.09	28.29	12.2	25.3	20.5	Bimodal	−0.53
MED-4	23.68	18.63	26.96	8.33	24.9	22.5	Bimodal	−0.28
KAMC								
CARD-1	23.49	18.96	29.24	10.28	21.3	25.9	Bimodal	−0.58
CARD-2	21.71	16.44	30.9	14.46	21.8	—	Right-skewed	−0.23
CARD-3	23.12	20.07	26.77	6.7	21.2	24.7	Bimodal	−0.09
CARD-4	23.61	18.69	29.78	11.09	23.8	—	Left-skewed	0.37
CARD-5	21.59	17.86	27.2	9.34	20.1	25.3	Bimodal	−0.62
ONCO-1	26.46	20.27	30.34	10.07	26.8	—	Left-skewed	−0.42
ONCO-2	23.04	17.92	28.62	10.7	24.1	—	Left-skewed	−0.45
ONCO-3	23.92	19.4	28.02	8.62	25.8	23.1	Bimodal	−0.37
ONCO-4	24.58	17.47	27.45	9.98	25.3	21.2	Bimodal	−0.13
ONCO-5	24.59	18.88	27.35	8.47	25.4	21.9	Bimodal	−0.27

* The correlation of T_a and Rh measured by Spearman's method for non-parametric data.

3.3.2. KAMC (Double-Occupancy Beds)

Similarly, the KAMC wards manifested three regular patterns: bimodal, right-skewed, and left-skewed (Figure 8). At the cardiology ward, three rooms (CARD-1, CARD-2, CARD-6) had similar first modes at 21.3, 21.8, and 20.1 °C, respectively. The other two rooms recorded 25.2 and 23.8 °C. Based on the literature, cardiovascular patients are affected by extreme external temperatures; some studies investigated the correlations between high temperatures and mortality rates [55–57] and increasing admission to hospitals [58–60]. It was expected for this population group to opt for neither very hot nor very cold. It was interesting to note that even if the patient rooms in KAMC were double occupancy, the T_a still demonstrated regular patterns and that no uniform and multimodal distributions were observed. By contrast, the oncology ward showed higher modes of 26.8, 24.1, 25.8, 25.3, and 25.4 °C in ONCO-1, ONCO-2, ONCO-3, ONCO-4, and ONCO-5, respectively.

3.3.3. Statistical Interpretation

With the exception of the CARD rooms, whose temperatures tended to be between 20 and 21.8 °C, all temperature peaks in the other wards shifted to warmer conditions. The left-skewed rooms indicated that a few outliers were detected among T_a from 17–19 °C (e.g., ONCO-3 and ONCO-4), thereby revealing the capability of the HVAC system to reach minimum temperatures with unnecessary cooling demands. These distributions were checked to see whether any relationships were caused by other controlling (independent) variables that the patients experienced, such as month, type of ward, and time of the day. The mixed-effects model allowed us to predict the variance attributed to each room. The effect of T_a was assumed to vary per room. Hence, a random intercept was used. This assumption came from the fact that the rooms were occupied for four months by a variety of patients who had varying temperature preferences during their hospitalization.

To ensure that the model enhanced the prediction of T_a by enabling the intercept to vary per room, three sets of baseline models were created. **Model A** only integrated the random intercept, while **model B** added the time of the day. The time of the day was classified into four periods: morning (07:00 to 11:00), afternoon (11:00 to 16:00), late afternoon (16:00 to 19:00), and night (19:00 to 07:00). The third model, **model C**, integrated the time of the day and the relative humidity. ANOVA was used to compare the three models, and the findings indicated that all of them were statistically significant ($p < 0.05$). **Model C** was selected to carry out the analysis due to the low Akaike information criterion (AIC), an estimator of the information lost by the model, which posits that less is more [61]. R^2 was computed for the mixed-effects model using [62] to explain the effects of independent variables (time of day, Rh) on the variance of T_a. This method is in line with [63–66].

As a result, each hospital fitted its own model. Hence, R^2_{IMC} and R^2_{KAMC} interpreted 15 % and 18% of the variance of indoor temperature, respectively. The temperature intercepts were 28.45 °C at IMC and 28.49 °C at KAMC. Table 6 shows the results of the mixed-effects model in both hospitals. At IMC, a decrease in relative humidity of 1% for all of the rooms was associated with a decrease in indoor temperature of 0.14 °C (95% C.I. = −0.14–0.13), similarly to KAMC. These small variations indicated that time of the day and relative humidity had no major influence on the patients' perceived temperatures. Ultimately, this led to the main conclusion that the patients perceived warmer conditions during their hospitalization and that this perception is not attributable to either the changes of T_a at a particular time of the day or to the increase/decrease of relative humidity. In addition, it showed the efficient HVAC system's capacity to reduce the impacts of extreme external climates in the patients' rooms. Other variables were also tested, such as month, type of ward, and T_a shape of distribution. All had insignificant contributions to enhancing the predictive ability of **model C**.

Table 6. Results of indoor temperature predicted by the mixed effects model in patient rooms at IMC and KAMC (SE: standard errors, CI: confidence interval at 95%).

Hospital	Variable (Fixed)	Coefficient (Estimates)	SE	CI (95%)	
				Lower	Upper
IMC	Intercept	28.45	0.16	28.18	28.90
	Morning	−0.03	0.03	−0.09	0.02
	Afternoon	−0.15	0.03	−0.19	−0.17
	Late afternoon	−0.24	0.02	−0.21	−0.09
	Night	−0.21	0.03	−0.29	−0.20
	Rh%	−0.13	0.00	−0.14	−0.13
KAMC	Intercept	28.49	0.29	27.86	29.11
	Morning	−0.13	0.03	−0.20	−0.06
	Afternoon	0.11	0.02	0.03	0.19
	Late afternoon	0.13	0.04	−0.19	−0.08
	Night	−0.13	0.01	−0.13	−0.09
	Rh%	−0.13	0.00	−0.14	−0.13

3.4. Discussion

This research went beyond common studies that measure correlations to detect the differences in internal temperatures of patient rooms. It sought to pinpoint any regular profiles of indoor temperature across several rooms occupied by many patients. In well-controlled hospitals, such as the IMC and KAMC, the patients each have a thermostat that gives them a sense of control to thermally adapt their indoor environment [67]. However, other information should be taken into consideration, such as the time of medication administration and its impact on the patients, especially on those whose medications exerted side effects. There are adverse effects of thermal discomfort on patients, such as general issues of thermo-physiology, blood flow, regulatory response, and thermal sensing, which may lead to health-related consequences [24]. The extended duration of monitoring gave us an indication of how the patients' behaviors towards indoor temperature varied. All patient rooms in the same ward, such as SUR, were found to have very similar profiles, with the mode of T_a showing very similar temperatures of 22.2–23.9 °C. Meanwhile, MED showed bimodal T_a patterns of 24.8–25.3 °C. In the ONCO rooms, it is interesting to note that even with the double occupancy per room, the ONCO patients still preferred warmer temperatures (modes varied from 24.1 to 26.8 °C). Ultimately, all patient rooms demonstrated the same wide range noticed during the measurement period. The average range for each ward was SUR (10 °C), MED (8 °C), CARD (12 °C), and ONCO (9 °C), respectively.

One dilemma in thermal comfort studies in hospitals is that the use of common thermal comfort indices similar to those employed in other buildings is not sufficient to provide an understanding of patient behaviors and needs that are affected by the acuteness of their medical conditions and other potential underlying factors. For instance, the transverse approach is inappropriate due to its limitations in capturing the indoor temperature within a time span of only a few minutes (5–10 min). Moreover, it does not take into account low-insulating clothing (uniforms) and decreases in body metabolism. For example, although several patterns were identified among the rooms, thermal satisfaction still cannot be anticipated, as the results of TSV and TPV only capture certain moments of patient experience during hospitalization. One of the essential findings in our research was that four out of five CARD patient rooms recorded lower mode temperatures of 20.1, 21.2, 21.3, and 21.8 °C.

The concept of a neutral (comfort) temperature is inadequate for this kind of population due to inconsistent temperature amplitudes. Additionally, this raises a question of whether patients face ideal situations during their stay. Although the longitudinal method is very limited in hospital-related research, it would be ideal in enabling us to detect the changes of indoor temperature over certain periods. There is no doubt that patients lean towards warmer conditions, but thermal comfort research in hospitals needs to identify patient groups' requirements and thermal ranges based on several health and medical indicators, in order to develop a modified PMV model that can account for those circumstances. This work is an initial step toward interpreting how patients perceive indoor temperatures as a dominant variable of thermal comfort.

Optimizing the heating and cooling loads of buildings is one of the major purposes of thermal comfort standards, aside from maintaining the indoor environment [68]. Knowing more about human thermal comfort informs this optimization and also increases people's satisfaction [69]. In hospitals, among hospitalized patients particularly, the period of hospitalization needs to be taken into account by knowing all of the patients' requirements regarding their indoor environment and how other underlying factors do, or do not, interfere with the building performance itself. A scheme is required similar to that of performance-based building (PBB), which is a building design environment incorporating all the involved decision-makers to ascertain the long-term efficiency of the building [70].

4. Conclusions

This research sought to: (a) appraise the indoor temperature profiles (distribution of shapes) in selected patient rooms among various inpatient wards over an extended period of time; (b) determine whether those profiles had regular peaks (modes) that indicated temperature tails towards cold, hot, or neutral; and (c) explore the perceptions of thermal environment of a large sample of hospitalized patients. Over 18 general patient rooms in four general and specialized wards were longitudinally monitored for four continuous months in 2018 at IMC and KAMC in Saudi Arabia. In parallel, 522 TSVs and TPVs were obtained for 522 patients using bilingual (Arabic–English) surveys, aside from their health information. A summary of the findings is as follows:

1. The bimodal shape, as a common distribution, indicated that two modes of indoor temperature were experienced by the hospitalized patients (12 out of 18 patient rooms).
2. Warmer temperature peaks, represented by mode, were desired at medical and oncology wards (24.8, 24.9, 25.2, and 25.3 °C; and 25.3, 25.4, 25.8, and 26.8 °C, respectively).
3. Cooler temperatures modes (left-skewed shape) were noted for the cardiology ward (20.1, 21.2, 21.3, and 21.8 °C).
4. Moderate temperatures were shown in SUR rooms (22.9, 23.2, 23.9, and 24.1 °C); those values were fitted to the set-point design range.
5. Around 15% and 18% of indoor temperature can be explained by independent variables (time of the day, Rh) at IMC and KAMC, respectively.
6. At IMC and KAMC, 72% and 67% of TSVs were found in the vicinity of (−1 and +1) respectively, indicating that the indoor environment was not satisfactory at IMC or KAMC.

7. At IMC, 71% of TPVs demanded comfortable conditions, 25% preferred cooler temperatures, and a few sought warmer conditions (3%). Similarly, at KAMC, 70% wanted comfortable environments, 12% asked for cooler conditions, and a few requested the rooms to be warmer (17%).

Ultimately, more effort needs to be exerted to identify all of the underlying factors related to patients' thermal environments during hospitalization, such as the medical procedures undertaken from admission to discharge, the recovery processes, and certain medications that raise patients' metabolisms. A better understanding of the indoor environment dispensary in wards will provide more detailed information of how patients are likely to perceive indoor temperatures. Such work will inform explicit cooling strategies that accommodate different patient groups and reduce massive energy loads that are not exploited by patients. The tendency of preferred temperatures towards warmer conditions in summer means that the set points may not be optimized, and the buildings over-cool to try to meet lower set temperatures than are preferred by patients. It is recommended that building monitoring systems (BMS) greatly improve the monitoring of revised set point temperatures without over-compensating; besides, it has other features to control the indoor environment variables. That can inform future work to modify a system's capability by shifting the design range to the warm side and to provide significant implications on how patients' thermo-physiologies respond to the ambient environment. Such information will contribute to the development of guidelines for the more optimal design of HVAC systems for patient rooms in hospitals.

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Abbreviations

IMC	International Medical Centre
KAMC	King Abdullah Medical City
SUR	Surgical ward
MED	Medical ward
CARD	Cardiology ward
ONOC	Oncology ward
TSV	Thermal sensation vote
TPV	Thermal preference vote

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