Statistical Evaluation of Tolerance to Indoor Temperature Fluctuations for Different Lengths of Stay for Cardiovascular Inpatients

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ABSTRACT
Elevated external temperatures highly affect cardiovascular patients and lead to increased hospital admissions. However, very little is known about what impact fluctuations in indoor temperature have on this patient group in any setting. Inherent difficulties in gathering data from this group of patients directed led to developing this research to investigate the relationship between hospital length of stay (LoS) and cardiovascular inpatients' tolerance to indoor temperature fluctuations. Data collection and analysis involved measuring indoor air temperatures and relative humidity for four months in cardiology and cardiac surgery wards within a hospital in Saudi Arabia occupied by 67 patients. A mixed-effects model was used for data analysis. It considered LoS and gender as fixed effects and differences between patients as a random effect. The evidence shows irregular variations of 1.42 ˚C of indoor temperature for patients that experienced different LoS, and 2.7 ˚C random deviations due to unknown factors. Indoor temperature was inconsistent across the various LoS categories and gender by around ±1 ˚C. In this study, the indoor temperature had no statistically relevant variations during varied LoS of cardiovascular patients, suggesting that patients experienced a wide range of indoor temperatures as a result of other interrelated factors. However, LoS explains 21% of the variations in indoor temperature. Also, opportunities for patients to acclimatize were limited due to significant deviations in internal temperature. The variations observed in hospitals are likely to be experienced by chronically diseased dwellers. Therefore, dwelling design guidelines must be revisited to incorporate enhanced principles of thermal comfort.

Keywords: *Hospital, length of stay, mixed-effects model, indoor temperature, cardiovascular inpatients*

1. INTRODUCTION

The negative effects of exposing cardiovascular patients to extreme temperatures are various, and ultimately, it leads to premature death. In this respect, recent variations in global climatic conditions have contributed significantly to adverse health issues across the world [1]. Key indicators from interdisciplinary research have quantified the consequences of increasing outdoor temperature on human health, namely, higher mortality rates during heatwaves [2], [3], morbidity including heat-related illness [1], [4], [5], and increasing overall admission rates to hospitals [6]. Studies have shown that these anticipated health effects are substantial, and the consequences extend to indoor exposure. The most vulnerable groups are infants, the elderly, people suffering from cardiac or respiratory diseases, and people in non-air-conditioned spaces [7]. Bunker et al. [3] also stated that increasing danger of cardiovascular, cerebrovascular and respiratory mortality could be associated with heat exposure. Another study [8] highlighted that people with cardiovascular disease-related conditions are more vulnerable to heat variation. The known direct correlation between heat waves and increased hospitalisation [9] indicates that dwellings can be failing to protect vulnerable groups from extreme outdoor heat variations. Minimal chances for recovering are given to patients if hospitals also fail to protect them from heat variations during hospitalization.

An alternative for observing the impact of the physical environment on patients is to observe patients' length of stay (LoS) during heatwave events. Hospital LoS is defined as "an important indicator of the use of medical services when assessing the efficiency of hospital management, patient quality of care, and functional evaluation" [10]. Research observing the length of stay within hospitals is abundant and multi-disciplinary. For example, in health and clinical research, patients are generally classified by their medical condition or admission unit [10] so that LoS baselines can be set per patient group. LoS has been studied for patients with cardiac-related diseases for different factors such as temporal changes in older patients [11], atherosclerosis risk [12], and blood transfusion [13]. Other studies investigated the impact of certain diseases and admission units on the LoS such as comorbidity of mental illness [14] psychiatric wards [15], [16], the intensive care unit (ICU) [17], [18], hip fractures [19], and chronic obstructive pulmonary disease (COPD) [20]. From a management perspective, there have been many hospital initiatives seeking to reduce the average LoS for patients by implementing several administrative processes such as, enhancing internal protocols and developing alternative services [21] to reduce the pressure on bed capacity.

Apart from lighting research, that has some psychological impacts that might speed up the recovery process (Table 1), no framework has shown how other characteristics of the physical environment could be linked to the LoS.

Table 1. Findings of LoS research related to the physical environment.

Study	Indicator	Size of trial/medical condition	Main findings/ impact of indicator on LoS
[22]	Daylight illumination	263 (post-surgery patients)	Multiple linear regression was applied to maintain explanatory variables fixed such as heart rate, diabetes mellitus, mean arterial pressure, and outdoor view. When the intensity of daylight at head position raises by 100 (lx), a potential reduction of 7.3 hours LoS is proved.
[23]	Window views	46 patients	Forty-six surgical patients assigned into two groups of views, one group sees natural scenery, and a second group sees a brick wall. The patients with a view of natural scenery had a shorter post-surgery hospital stay and less negative comments in comparison to the other patients.
[24]	Sunlight	602 (unipolar & bipolar inpatients)	Bipolar inpatients in east rooms were stayed shorter (3.67 days) compared to those in west rooms. Patients in east rooms were exposed to direct sunlight in the morning. However, no significant effect was revealed for unipolar inpatients.
[25]	Sunlight	174 admissions	LoS was compared between depressed patients in sunny rooms and dull rooms. Patients in sunny rooms had shorter stay (16.9 days) than those in dull rooms (19.5 days). This result shows a statistically significant difference (2.6 days).
[26]	Daylight	1167 admissions	A total of 25% of analysed data showed that rooms in a brighter environment (in the SE area) were found to have shorter patient LoS as compared to rooms in the NW are by 16% by when 25% of the comparison sets were considered.

Existing research in this field contains various limitations, such as the homogenisation of patient profiles. Except for a few researchers, such as Joarder and Price [22], most built environment research fails to systematically acknowledge interrelated factors such as illness, prognosis, surgery status, acuity of illness, demographics distribution or the interaction with the surrounding environment [26]. Also, despite the substantial amount of medical research, a cause-effect relationship between the built environment and health outcomes has never been established [27]. Thus, identifying and organising these factors represents a step-change in the research approach that can lead to advancing our understanding of the relationship between health and the built environment. For appropriately profiling is likely to eliminate errors and to produce more representative findings. Thus, using the LoS as an indicator of health outcomes for specific patient profiles represents an opportunity for advancing this area of knowledge as, to date, no studies have examined LoS and the thermal comfort of specific patient groups.

The research approach taken builds on previous research [28] investigating the impact of LoS on perceived indoor air temperature for cardiovascular patients' during hospitalization using spot measurements. It extends previous work by extending the measurement of indoor temperature to 4-months. Also, patients' LoS was classified into different time bands: 2-3 days (LoS-2), 4-6 days (LoS-3), more than a week (LoS-4), and more than a month (LoS-5). Single-day stays are automatically excluded following protocols in this field [29]. The rationale for such division includes: very few studies have been conducted to investigate the effect of Indoor Environmental Quality (IEQ) aspects on the LoS, and these have concentrated mostly on lighting research and not the impact of fluctuations in indoor temperature; The LoS is commonly represented as a health outcome index in the literature [26], which is not the case in this research; and short periods of stay (1-2 days) cannot reveal significant differences in indoor temperature fluctuations, so different categories were created to examine patient tolerance over extended periods of hospitalisation.

Subsequently, the indoor temperature was examined against selected LoS time bands to determine patients' tolerance to fluctuations in indoor temperature independently of all inter-related factors except for gender. This work is not intended to use LoS as an index of health outcomes but to show how patients perceive indoor temperatures over time. Therefore, the objectives of this research are:

(1) To determine if the perceived fluctuation in indoor temperature differed significantly

among patient rooms in the same LoS time band, or across all categories.

(2) To reveal the impact of the LoS on patient perception of indoor temperature and how this experience changed for short or long periods of stay.

2. RESEARCH METHOD

This study was undertaken at the King Abdullah Medical City (KAMC), a public, specialist hospital in Makkah, Saudi Arabia during May, June, July, and August of 2018. The KAMC was selected due to its specialist cardiology and cardiac surgery wards, and due to their accreditations in medical care and quality management at national and international levels [30]. The hospital design and construction are typical for Saudi Arabia standards. It is five stories high, with inpatient wards located on the 3rd and 4th floors. The outdoor temperature data (Table 2) shows that the historic hospital outdoor temperature ranges from 28.9 to 43.9 °C at 99% of the time (i.e. excluding heatwaves).

Table 2. Historic monthly summary of external temperatures (T_{out}) and humidity (Rh_{out}) during the data collection (source: Department of Meteorology, King Abdul-Aziz University in Jeddah).

Month	T_{out} (°C)			Rh_{out} (%)		
	Min.*	Mean	Max.	Min.	Mean	Max.
May	28.9	35.1	43.2	17.8	20.7	47
June	30.9	36.8	44	18.6	20.6	45.7
July	30.9	36.4	43.5	19.5	20.8	48.7
August	31.1	36.2	43.9	27	23	65.1

*Minimum and maximum outdoor temperature and humidity based on the daily average of min/max.

Data collection involved conducting a patients' survey focused on perceptions of thermal comfort perceptions for the investigated period; gathering the LoS records for participating cardiac patients; and the monitoring of indoor environment variables (indoor air temperature and relative humidity) from May – Aug 2018. These are further explained in the following.

For the survey, a total of 67 patients (Table 3) agreed to participate by completing questionnaires during their hospitalization and the indoor environmental data monitoring. Informed consent was sought from each patient or their relative(s) in case of difficulty in reading or writing. The questionnaire was designed to gather information about thermal comfort within patient rooms, according to ASHRAE-55 [31] and ISO 7730:2005 [32]. Questions were written in English and translated into Arabic for accessibility. The questionnaire was handed to patients in the first instance to answer the questions. In case of inability to write, the patients were interviewed either by the researcher or their accompanying relative(s). Table 3 lists the demographic mix of patients involved in the study participated.

Table 3. Demographics of participated patients.

Age group	18-24	25-34	35-44	45-54	55-64	65-74	>75	Total
Male	1	2	7	10	13	10	4	47
Female	-	2	3	1	6	6	2	20
Total	1	4	10	11	19	16	6	67

Concerning LoS records, these were obtained from authorised chief nurses who gathered admission and discharge dates for participating patients in each ward. Subsequently, the LoS records were organised into the proposed four bands by gender (Table 4), being single-day admissions omitted as referring to outpatients. This stratification approach enabled the examination of how hospitalised patients are acclimatised to their room temperature based on LoS. Also, it tests the hypothesis which is; patients who stay longer can have a narrowed range of indoor temperature compared to those who stay shorter.

Table 4. Patient length of stay collated by patient gender and age groups.

Category		Length of stay bands (LoS)			
		2-3 days (LoS-2)	4-6 days (LoS-3)	> week (LoS-4)	> month (LoS-5)
Gender	M	14	8	21	4
	F	6	6	7	1

2.1. Monitoring strategy

With regards environmental data monitoring, a kit consisting of a Raspberry Pi + 3 data-loggers (Table 5) was installed in each of the 13 patient rooms within the cardiology and cardiac surgery wards investigated. The monitored rooms are fully air-conditioned (central HVAC system), and patients can control room temperature through the use of a thermostat. These rooms were designed in full compliance of ventilation requirements for healthcare facilities in ANSI/ASHRAE-170:2013 [33], and chapter 20 in 2017 ASHRAE Handbook—Fundamentals [34]. Indoor air temperature (T_a)°C, and indoor relative humidity (Rh) % were recorded for four consecutive summer months (May, June, July, and August) in 2018 (Table 6). T_a was monitored in 5-min intervals and subsequently aggregated into 30-min intervals by averaging the five readings due to very identical readings between the previous and next readings.

Table 5. Raspberry Pi technical specifications.

Sensor	Parameter	Accuracy	Range
Raspberry Pi sensor	Air temperature (DS18B20)	±0.5	-10…+85°C
	Relative humidity (RHT03)	±2%	0…100% RH

Table 6. Summary of indoor air temperatures and relative humidity in patient rooms per LoS band during the data collection. (data are minimum, maximum, means and SD: standard deviation).

Variable		Length of stay (LoS)			
		2-3 days (LoS-2)	4-6 days (LoS-3)	> week (LoS-4)	> month (LoS-5)
T_a °C*	Min.	20.29	19.93	17.28	22.28
	Mean	22.78	23.21	23.27	22.97
	SD	2.88	3.22	3.16	3.21
	Max.	26.07	28.87	26.20	24.41
Rh %	Min.	25.58	26.26	25.52	29.98
	Mean	37.39	33.55	33.85	33.60
	SD	7.16	4.50	4.57	2.42
	Max.	51.04	40.64	42.98	35.62

*T_a: is the mean of each patient stay among all LoS groups.

2.2. Data analysis

Indoor temperature and LoS data were analysed through a mixed-effects model where T_a was the dependent variable, and the four LoS categories and gender were independent variables. Each category had a set of patients. The pre-defined requirements and assumptions, such as normal distribution, multi-collinearity and non-independence of the observations, were all met. For flexibility and full data points consideration [35], all fluctuations in indoor temperatures and LoS band for all patients (each patient stay was considered separately) was visualized by plotting T_a versus LoS. All patients had their room temperature measured every 30 min during their stay. All collected data were examined using the *'lme4'* package [36] in R statistical-software [37], [38]. Before conducting the analysis, the normal distribution of T_a and Rh was checked for each patient duration of stay by computing the Shapiro–Wilk normality test [39], which required a p-value > 0.05 to prove that the data came from a normal distribution. Following this approach, it can be expected that results will reveal discrepancies of indoor temperature during hospitalization. The analysis of such discrepancies required two approaches.

Firstly the statistical analysis of the data involved the use of a random-effect model. The random-effects model has two types—random intercept and random slope; these were used to meet the desired objectives of this research. The random intercept model was used to interpret the T_a baselines amongst the LoS categories because the model intercept may vary from patient to patient, indicating random effects amongst patients. The random intercept model aims to measure the correlation between patients in a static way, which is not the case in the present study.

The variability of indoor temperature amongst patients is, in reality, caused by complicated factors (residual variation). One feature of this model is its ability to consider the variation amongst other examined variables. T_a (the response variable) was explained by fitting the LoS and gender as the fixed effects variables (the controlled variables in the experiment). In contrast, the inclusion of the random effect variable (patients) accounted for individual patient variations. In other words, this was done by assuming a different baseline T_a for patients who had a different intercept at the same LoS category. To examine the variance in T_a, Equation 1 was applied in the analysis,

$T_a \sim LoS + gender + (1|Patient) + \epsilon$ (Equation 1)

Where (1|Patient) indicates that each patient had their intercept of LoS and T_a, and 'ε' accounted for the deviations of the other random factors from T_a and could not be controlled experimentally, such as the interaction between medications and other hidden factors related to patients. The addition of gender as a fixed effect was due to the preference of females for a higher indoor temperature compared with males because of physiological differences [40], [41], [42]; however, this could not be pursued in hospitals because of other medical or clinical factors [43].

Secondly, for assessing the effect of length of stay (LoS) on T_a there has been much discussion and several approaches regarding the computation of the significance of mixed effects models (p-value) [35], as there is no direct and easy way to calculate the p-value. This issue was considered before conducting the analysis by ensuring that adequate data points represented indoor temperature for any single patient's stay (minimum recorded data points: 24) to ascertain that reliable results were obtained. This study used the likelihood ratio test (LR) [44] to assess the likelihood of two models: the original model that fixed the LoS (Section 3.2.1) and the reduced model that lowered the LoS. The formula of the reduced model is shown in Equation 2, whereas the original model is presented earlier in Equation 1. The result of the LR test of the original and reduced models was:

- Chi-square value $\chi^2(3) = 6.92$
- p-value = 0.07
- Degree of freedom = 3
- Not statistically significant

Denoting that the LoS a weak influence on the indoor air temperature of the patients' rooms. Another method to report the influence of LoS was by diving the total variance of patients including residuals on the variance of patients, only 21% of the variances among patients' T_a were detected by the LoS.

$T_a \sim gender + (1|Patient) + \epsilon$ (Equation 2)

3. RESULTS

3.1. Distribution of T_a

The normal distribution of two data-loggers in the LoS-2 category and two others in LoS-4 category were excluded from further analysis due to many outliers (data points that were higher than 1.5 times the interquartile range), as they were clearly measurement errors. T_a ranges varied between 13.85 ˚C and 32.52 ˚C and Rh varied between 14-88%. An estimation of the cumulative distribution (ECDF) of T_a across each LoS category is shown in Figure 1. T_a readings show that the temperature ranged between T_a >16 ˚C and T_a<30 ˚C across all LoS bands. Between 75% and 80 % of all T_a were within 24–26 ˚C. The average of T_a across bands were 22.81 ˚C, 23.21 ˚C, 23.28 ˚C, and 22.97 ˚C for LoS-2, 3, 4 and 5 respectively.

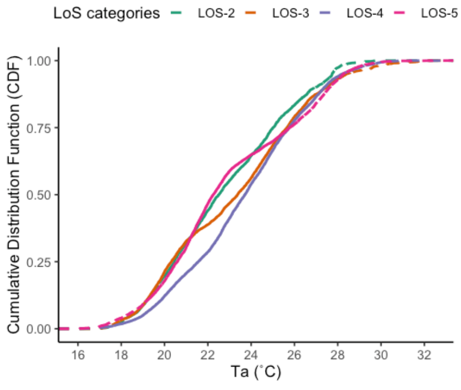

Figure 1. ECDF plot of indoor temperature per LoS category.

Figure 2 shows that room temperature fluctuations were inconsistent for all patients' categories, in particular those who stayed longer, and which are subject to rapid acclimatization. It implies that patients were consistently using air-conditioning to adjust the room temperature. There was considerable T_a variation across all patients' stays within all LoS categories. This is also valid for the stratified analysis of LoS-4 group, which was larger than others, but also had a T_a variation (SD = 3.15). The results indicate that individual thermal comfort preferences can be significantly impacted by the patient health condition and their LoS. However, this research does not provide a basis to ascertain how T_a was perceived according to longer or shorter duration of stay, to explain T_a variations across LoS categories, and whether the LoS affected the way the patients perceived T_a.

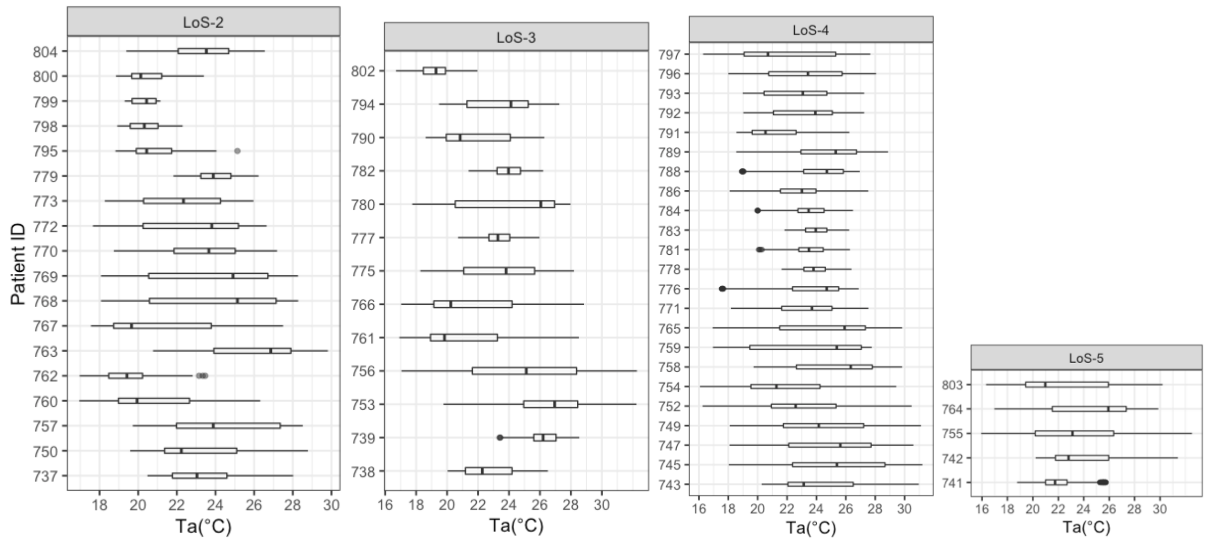

Figure 2. Variability of indoor air temperature among patients at all LoS categories. (Patient ID is an identification number for each patient stay in each LoS category)

3.2. Discrepancies of indoor temperature during hospitalization

3.2.1. Statistical analysis

Table 7 shows a summary of random statistical effects. The standard deviation (SD) column is a measure of the variability of T_a for all patients in all LoS categories for the same unit of T_a (°C). The output of indoor temperature variability was the variance for the fixed effect in the model, representing the four levels of LoS and two levels of gender. Table 7 showed the variances among patients by 1.42 °C.

Table 7. Summary statistics of model outputs.

Random effect			
Groups		Variance	SD
Patients	intercept	2.01	1.42
Residual		7.33	2.70
Fixed effect			
	Estimate	Std. Error	t-value
Intercept	23.26	0.45	51.50
LoS 2–3	0.71	0.52	1.36
LoS 3–4	1.21	0.45	2.70
LoS 4–5	0.80	0.72	1.11
Gender M–F	-1.13	0.41	-2.74

In other words, the variance of T_a was dispersed; neither an explicit increase nor decrease in the categories was observed when the patients stayed shorter or longer, nor narrow ranges of T_a were seen amongst the patients themselves. It was surprising that although LoS-4 had the largest sample of patients, the differences in T_a were still idiosyncratic. The '*residual'* value in Table 7 denoted the deviation of T_a by 2.7°C, and this was not caused by a fixed effect (LoS and gender). This dispersion of T_a was attributable to many interrelated factors, either medical or psychological, which were experienced by the patients even if they were able to adjust their room temperatures. Unfortunately, this could rarely be ascribed to LoS only, and such a topic is outside the scope of the present study. On the other hand, the fixed effects coefficients '*estimate'* referred to the slope of the categorical effect of gender and LoS as follows:

- The Indoor temperature was slightly higher in LoS-2 than in LoS-3 by 0.71 °C.
- The indoor temperature in LoS-3 was 1.2°C higher than in LoS-4.
- The Indoor temperature in LoS-4 was 0.8°C lower than LoS-5.
- The Indoor temperature was lower for females than males by 1.13 °C.

Therefore, this dispersion demonstrated that T_a did not vary significantly among gender and LoS categories. This can be seen in the standard error, which was so close to coefficient values. The intercepts of all patients (23.26 °C) were found halfway between males and females and the LoS categories as seen in Table 6. Random effect coefficients indicated that the majority of patients T_a were reasonably far from the intercept point (0), which is the estimated value of T_a (response variable) on all LoS categories. A descriptive summary statistics of T_a among all LoSs was presented in Table 8.

Table 8. Descriptive summary statistics of indoor temperature against LoS categories.

LoS	Data points*	Mean	SD	95% Confidence interval		p-value
				Lower	upper	
LoS-2	3870	22.78	±2.88	22.69	22.87	P < 0.000 (significant)
LoS-3	5368	23.21	±3.22	23.12	23.30	P < 0.000 (significant)
LoS-4	14824	23.27	±3.16	23.22	23.32	P < 0.000 (significant)
LoS-5	6681	22.97	±3.21	22.89	23.04	P < 0.000 (significant)

*Number of indoor temperature measurements in each LoS category

4. DISCUSSION

This work is an initial step to interpret how patients perceive indoor temperatures as a dominant variable of thermal comfort. Duration of stay does not give us any indication of how patients' behaviour toward indoor temperatures is discrepant. In contrast, some patients were found to have similar perceptions in each LoS category; the perceptions of others mostly recorded a significant standard deviation, meaning that several changes occurred.

Using LoS as an index of health outcomes ignored many variables that contribute either positively or negatively to health outcomes. The priority was to examine the physical environment by observing all or most of the factors that might affect patient thermal comfort and to establish a clear picture of how certain of those factors can affect a health outcome index. Due to an absence of any study matching thermal comfort to the LoS, which is used by other health and medical research as an indicator for recovery speed, selected examples from lighting research were chosen to demonstrate how those methodological approaches were poor when they tried to link lighting to the LoS. In hospitals, among hospitalised patients particularly, the period of hospitalisation needs to be taken into account by knowing all patient requirements regarding their indoor environment and how other underlying factors do or do not interfere with the building performance itself.

From a theoretical point of view, research about LoS and thermal comfort can be underpinned by the *Stress and Adaptation Theory* [45]. As such, research and theory associated extremes of temperature, sound, and other environmental variables with stress and coping or adaptive behaviours that reduce stress or its impact. A distinction exists between acute and chronic environmental stressor factors. In the context of this research, a heatwave is considered an acute stressor while general gradual global warming is a chronic one. From an epistemological perspective, there is still a lack of explicit cause and effect relationships [27].

Consequently, this study also uses correlational relationships that do not take into account possible confounding variables. In other words, while profiling supports advancing our knowledge in this field, design inherently generates too many variables and relationships between the built environment and health outcomes that can be empirically tested. In this respect, sources of indoor temperature variation are well known. They range from macro issues such as terrain condition, altitude and inappropriate building orientation and cladding systems exposing building façade to extreme solar radiation and micro issues such as inadequate equipment. Thus, investigating any spatial attribute or arrangement that might affect indoor temperature is not part of this study because the unit of analysis is temperature variation independent of its source.

5. CONCLUSION

This study explored the impact of the LoS on cardiovascular patient experience of the indoor environment by monitoring the indoor air temperature for 67 patients during their stay, in parallel with collecting the LoS records, in the KAMC hospital between June–August 2018 period in Saudi Arabia. Patients were grouped into four categories of LoS for statistical analysis. The relationship between the LoS (explanatory variable) and T_a (response variable) was assessed using a mixed-effects model – specifically, random slopes. As fixed effects, the LoS and gender (applied without an interaction function) were added into the model. However, as random effects, patients' differences were treated as random slopes deemed the difference in their LoS. A summary of findings is as follows:

- The length of stay was weakly related to the variance of T_a among patient groups (p-value = 0.07, obtained by likelihood ratio test).
- The random intercept model showed that T_a differed insignificantly among patients by 1.42˚C in response to the LoS categories.
- T_a randomly deviated by 2.7˚C due to unknown factors.
- The average T_a of patient stays was 22.79 ˚C; the largest SD was 3.63 in LoS-4 and the smallest SD was 0.63 in LoS-2.

Further work can be conducted by establishing this relationship on a patient-monitoring system that captures patient signal vitals remotely. The outputs may then be linked to the indoor temperature measurements and other related variables composing a separate data profile for each patient. Resulting data will reveal how room temperature fluctuations may be correlated against patient signal vitals and how medical condition affects the internal heat balance for patients. Such information should contribute to the development of guidelines for the design of patient rooms in hospitals. It can also be extrapolated to the design of homes for older people experiencing cardio-related diseases, thus reducing or even avoiding hospitalisations and premature death. Regarding limitations, a larger sample size would better stratify patients into more discrete several groups based on age, gender or other health indicators. This would offer greater opportunities to reduce errors and bias arising from the measurements.

Ethical approval

The research proposal was approved by the Institutional Review Board (IRB) at KAMC no: 18-420 in 18th April 2018. Prior to that, EIRA1 form (Ethical Implications of Research Activity) has been approved by University of Bath, no: 1400, on 25th January 2018.

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