HO-18-003

# Using Thermal Comfort Models in Health Care Settings: A Review

**Rodrigo Mora, PhD, PEng**
*Associate Member ASHRAE*

**Michael Meteyer, PE**
*Member ASHRAE*

## ABSTRACT

*A fundamental challenge in assessing thermal comfort in health care settings is providing comfortable conditions for the diverse medical services and concurrent occupancy groups. Thermal comfort standards rely on thermal comfort models to predict thermal conditions in spaces that are satisfactory for human occupancy. However, thermal comfort standards and models have not been developed from experimental or field data in health care settings or with health-care-specific concerns in mind; therefore, their validity to assist in environmental health care design has been questioned. This study is motivated by the practical concerns with using thermal comfort models to assist in the design of HVAC systems for health care facilities.*

*The ASHRAE thermal comfort standard (ASHRAE 2017a) requires a set of environmental and personal factors that depend on the occupants' activity levels and clothing insulation. Outlined in this study are the challenges in providing thermal comfort in rooms with patients and medical staff with varying activity levels and clothing insulation. Other challenges explored include looking at activity levels that are near or above the research that was used to develop the comfort models and the lack of insulation values for the clothing required to be worn by some medical personnel. This study also reviews the complexity and diversity of patients, their levels of health, and the care they are receiving relative to the assessment of thermal comfort. A final complexity discussed is applying the steady-state thermal comfort models to the transient nature of occupants in health care facilities.*

*A literature review of thermal comfort research in health care settings is discussed and summarized. The focus has been on hospitals in general, with some studies on operating and patient rooms. A general conclusion points to patients being more tolerant of indoor conditions than predicted by the thermal comfort models and, generally, patients are more accepting of higher temperatures than the staff. The studies reviewed demonstrate that thermal comfort models can be applied with caution to rooms that serve medical staff and healthy patients—patients that are healthy in terms of thermal sensation and regulation.*

*This paper exposes increased complexities in addressing thermal comfort in health care settings and concludes that given the critical nature of health care facilities, as well as the levels of occupant diversity and specialization, increased detail and attention to individualities are needed. The paper also reveals a lack of personal and environmental data to enable reliable thermal comfort assessments.*

## INTRODUCTION

Thermal comfort is a subjective expression of our minds regarding the level of satisfaction with the thermal environment. It involves the combination of physics, physiology, and psychology expressed in terms of thermal sensation, thermal acceptability, and thermal preference. The mapping between thermal sensation, thermal acceptability, and thermal preference is an active subject of research (Keeling et al. 2016). Fortunately, humans tend to agree on a relatively narrow temperature range as comfortable under similar personal activity and clothing conditions (Fanger 1970; Gagge et al. 1972, 1986; Rholes 1973).

*ANSI/ASHRAE* Standard 55*, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2017a) was first published in 1966 and has been continuously updated and refined. The standard relies on various thermal comfort

**Rodrigo Mora** is a faculty member in the Building Science Graduate Program and program head of the Graduate Certificate in Building Energy Modeling at the School of Construction and the Environment, British Columbia Institute of Technology, Vancouver, BC, Canada. **Michael Meteyer** is a mechanical engineering manager at ERDMAN, Madison, WI, USA.

models for the prediction of thermal comfort in a variety of indoor environments. For mechanically conditioned buildings such as most health care facilities, the standard determines a range of acceptable conditions for thermal comfort for the majority (more than 80%) of the occupants based upon the predicted mean vote and predicted percent dissatisfaction (PMV-PPD) thermal comfort model (Fanger 1970, 1973). The PMV-PPD model, which is based on a steady-state thermal balance of the human body with the environment, has been validated using field studies. The PMV-PPD model requires two personal factors affecting body thermal balance with the environment, metabolic rate and clothing insulation, and four environmental factors—air temperature, radiant temperature, air speed, and humidity. The human and environmental factors must be applied together because the human response is tied to their interaction.

The PMV-PPD model, as used in ASHRAE Standard 55 (2017a), can be applied to healthy adults engaged in sedentary, nearly sedentary, or moderately active work, up to 2.0 met. Humphreys and Nicol (2002) found the field assessment of the activity rate and clothing insulation can lead to a significant source of error when applying the PMV-PPD model. Therefore, any assumed input parameters to the PMV-PPD model need to be selected carefully. Furthermore, Gauthier (2013) demonstrates through a sensitivity analysis that the PMV index appears more sensitive to the personal variables (metabolic rate and thermal insulation of clothing).

Two ASHRAE standards have purpose statements that mention providing thermal comfort: Standard 55, *Thermal Environmental Conditions for Human Occupancy* (2013a) and Standard 170, *Ventilation of Health Care Facilities* (2017b). English (2015) demonstrated that using the temperature and humidity requirements listed in Standard 170, in the PMV-PPD model of Standard 55, resulted in non-compliance. Standard 170 lists only a temperature and humidity range for various health care spaces. It is missing the two personal factors and two environmental factors (radiant temperature and air speed) that, according to Standard 55-2017, are considered critical to human thermal comfort. It can be argued that compliance with Standard 170 will not necessarily generate thermal acceptance by 80% or more of the occupants. That has generated some critical questions. Under what conditions is it appropriate to use Standard 55 to aid in the design of the thermal comfort conditions for health care facilities? Is the minimum target of 80% of occupants expected to be comfortable according to Standard 55 an acceptable threshold in health care settings?

## METHODOLOGY

ASHRAE Standard 55 (2017a) defines the term *representative occupant* is used to describe "an individual or composite or average of several individuals that is representative of the population occupying a space for 15 minutes or more."[1] Many of the medical staff have varying activities during a typical day and often spend less than 15 minutes in a given room. The purpose of the time requirement recognizes that it takes the human body some amount of time to adjust to the environment.

This study begins by identifying the representative occupants as prescribed by ASHRAE Standard 55 (2017a). It characterizes health care occupants in groups and subgroups and identifies the thermal comfort factors and challenges for meeting the environmental requirements necessary to satisfy the diverse occupants. That is followed by a critical review of the literature of using existing thermal comfort models in health care settings. This discussion is centered on the applicability of the PMV-PPD model to health care enviornments, which is arguably the most widely used thermal comfort model and is prescribed by Standard 55 for mechanically conditioned buildings. The review was broken down into the following topics:

- Studies by facility, department, or type of treatment
- Studies by occupant groups: patients and nonpatient

## REPRESENTATIVE OCCUPANTS IN HEALTH CARE

To apply the PMV-PPD thermal comfort model (ASHRAE 2017a) for each occupied space, the anticipated representative occupant groups are identified and categorized by similar metabolic activity and clothing insulation. The challenge in applying this comfort model to health care spaces is the diversity of representative occupants and, in some cases, the conflicting model-predicted temperature and humidity ranges between medial staff and patients who share a common space.

Occupants in health care facilities can be categorized into three main groups: medical and support staff, patients, and visitors. For each space, the environmental thermal requirements depend on the different representative occupants and the corresponding factors illustrated in Table 1. In this study, *service* refers to a medical or support service rendered in health care settings. Medical services include examinations, procedures, treatments, tests, diagnostics, therapies, consultations, and pharmaceutical services. Common support services include laboratory, sterilization, dietary, laundry, and housekeeping services. The environment should help promote the healing of patients (Van Den Berg 2005) and maintain the performance and arousal level of the staff (CIBSE 1999). For both patients and staff, the environmental and personal factors affecting thermal comfort are service specific. These factors affect the body's thermal balance. How an occupant reacts to the thermal balance involves many psychological factors related to the activity and/or the treatment that is occurring in the space. Furthermore, subgroups exist within the patient and staff occupant groups with more specific environmental

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1. ASHRAE. 2017a. ANSI/ASHRAE Standard 55-2017, *Thermal environmental conditions for human occupancy*. Atlanta: ASHRAE: pp. 2.

**Table 1. Health Care Thermal Comfort Factors**

| Thermal Comfort Factors | Staff | Patients | Visitors |
|---|---|---|---|
| Environmental: air temperature, radiant temperature, air speed, humidity | Medical/support service specific | Medical service specific | Common seasonal thermal adaptation |
| Personal: metabolic rate, clothing insulation | Medical/support service specific Limited adaptation/required clothing Activity: steady–transient | Medical service specific Gowning/bedding adaptation Standing, sitting, lying, sleeping, immobilized | Common seasonal thermal adaptation |
| Other: psychological, work related, health-condition related, etc. | Mental stress, fatigue, workload, performance, arousal, health condition, well-being | Anxiety, length of stay, health/ wellness condition, age, medication impact, healing, overall comfort | Anxiety, short stay |

concerns and factors affecting thermal comfort. This is discussed in the following sections.

Some common activity levels and resulting metabolic rates as well as clothing insulation values are provided in *ASHRAE Handbook—Fundamentals* (2017c). These are commonly cited in the comfort standards and in the literature, and their accuracies are a point of discussion. The Handbook states that for activities less than 1.5 met that are well defined, the accuracy is sufficient for HVAC engineering purposes. For less-defined activities at higher activity levels (greater than 3 met), the accuracy maybe in the ±50% range. The papers reviewed in this investigation included medical staff activity levels that resulted in assumed metabolic rates in the 1.2 to 1.7 range. Most of the activities cited are representative of common office-building activities that occurred when the research was done in the 1960s. Measured data on metabolic rates for various medical staff activities are needed to improve the accuracy and increase the confidence in the use of the current comfort models for health care thermal comfort design. Specific areas of interest where the occupants have higher metabolic rates are operating rooms and decontamination, laboratory, pathology, hazardous and sterile drug compounding, morgue, infectious disease isolation, and protective environment isolation areas.

In many of these areas, not only are the activity levels higher but the medical staff are also required to wear protective clothing. As Figure 1 illustrates, personnel working in the decontamination area wear protective clothing including a scrub uniform covered by a moisture-resistant barrier, shoe covers, rubber or plastic gloves, and a hair covering. During manual cleaning processes, when splashing can occur, safety goggles and a face mask should be worn.

Only one paper in the literature review (Cho et al. 1997) focused on clothing insulation in a health care settting, and it was limited to surgical gowns. Typically, authors use the clothing insulation (clo) factors referenced in *ASHRAE Handbook—Fundamentals* (2017c), which do not include specific

***Figure 1*** *Sterile processing protective clothing. Reprinted with permission of Marmaduke St. John/Alamy Stock Photo.*

measured clo values for the protective clothing listed. Data are needed on the thermal properties, thermal insulation, and vapor permeability of the different types of clothing used by staff in health care facilities and their actual use (how and when they are worn). Similarly, research data are needed on the effect of body movement on increased air velocity and clothing insulation. According to Havenith et al. (2002), the effects of body motion and air movement on clothing insulation are important and need to be accounted for in comfort prediction models. In many situations, there will be multiple representative occupants due to the varying activity levels and clothing insulation.

The scope for ASHRAE Standard 55 (2017a) includes healthy adults. Currently, there is no definition or discussion of what constitutes a healthy or unhealthy adult patient in the context of thermal comfort. Patients certainly cross the spectrum from healthy to unhealthy. In this context, healthy patients are those needing a laboratory test, a routine checkup, some medical procedures, or a small injury. As a patient's condition approaches an unhealthy condition, the comfort models' predictability become less certain. In some cases, patients may be on medication that affects their thermoregulatory response. Figure 2 summarizes the general factors affecting the thermal comfort of patients in three groups: age, medical condition, and type of service or medical procedure. As illustrated in Figure 2, assessing thermal comfort for patients is complex due to the number of factors involved.

Smith and Rae (1977) argue that at lower temperatures the arousal level of patients increases, and therefore they appear to complain more, whereas at higher temperatures there is more thermal acceptance even when the environmental parameters are outside the predicted comfort zone. Weaker patients preferred higher temperatures (Verheyen et al. 2011; Hwang et al. 2007).

Health care workers will make a patient as comfortable as possible. This may involve providing extra gowns or warming blankets or adjusting the room heating or cooling. Only a few studies have investigated patient bedding insulation as pointed out by Verheyen (2010). In designing the comfort temperature range for patient rooms where adding clothing or bedding is an option, the HVAC designer should consider the other representative occupants' cooling requirements.

Considering the staff, ASHRAE Standard 55-2017 requires a representative occupant to be in a space for 15 min or more. This issue is fundamentally concerned with the application of the PMV-PPD model, an inherently steady-state model, to transient conditions. The issue involves two aspects: the activity levels of staff (transient metabolic rates) and the short presence of staff in a given thermal environment (Skoog et al. 2005). Skoog et al. observed that the activities of staff in orthopedic wards vary throughout their work. According to Goto et al. (2002), steady-state models for the prediction of thermal sensation seem to be applicable after approximately 15 minutes of constant activity. For individuals engaged in moderate activities under moderate indoor environments, ASHRAE Standard 55 (ASHRAE 2017a) does not impose any limitations on activity changes but requires an occupancy period of no less than 15 minutes for spaces being assessed. There is a difference between rapid, stepwise changes in temperature and/or metabolic rates compared to slow frequency drifts and ramps and cycling variations in mechanically conditioned rooms. However, when the staff or patients are moving between rooms with similar temperature and the activity variations are not excessive, it is arguable that comfort models would apply to these spaces.

## LITERATURE REVIEW OF THERMAL COMFORT MODELS USED IN HEALTH CARE

Surprisingly, the focus of the literature has been on hospitals in general, operating rooms, and patient rooms. No thermal comfort research was found focusing on other types of

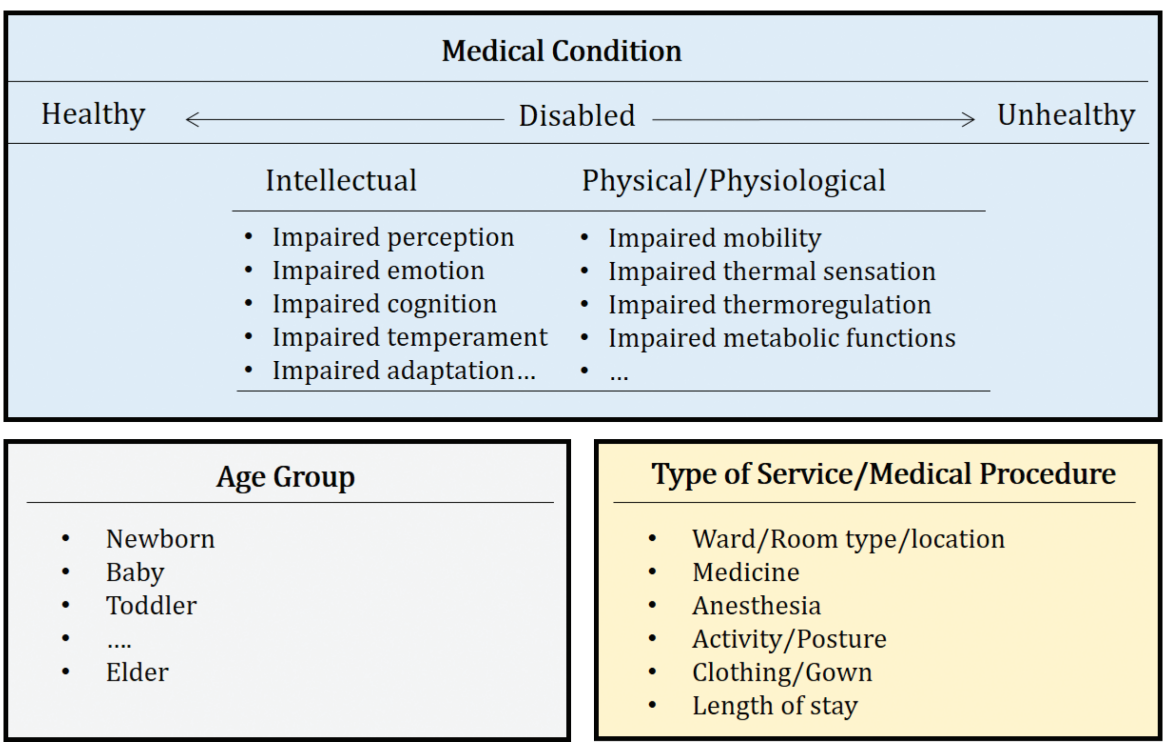


***Figure 2*** *Three groups of factors affecting thermal comfort for patients.*

facilities or rooms. Furthermore, no research was found on thermal comfort in specialized facilities such as children's hospitals, and no research was found on thermal comfort at the department level (e.g., emergency departments).

The studies reviewed characterize occupants generically using typical personal and environmental factors, with some describing individual clothing and activity levels. However, some specialized studies focus on the thermal comfort of particular groups of patients, such as patients with disabilities. Recently more attention is being given to studying the thermal comfort of elder patients.

Given the previously mentioned literature availability, the literature review in this study is organized as follows: a) by facility/department: general studies on thermal comfort in hospitals, studies of thermal comfort in operating rooms, and thermal comfort of patients in patient rooms, and b) by patient group: studies of thermal comfort on patients with disabilities and on elder patients.

## General Studies on Thermal Comfort in Hospitals

Table 2 summarizes field studies that apply the PMV-PPD model to hospital environments. Interestingly, all these studies originate in Asia and the Middle East, and except for one study in Iran, all of them focus on hospitals in the hot-humid climate of the tropics. These studies combine objective measurements of the environment, with most of them using subjective questionnaires to compare the thermal satisfaction of occupants versus the predictions by the PMV-PPD model.

From subjective questionnaires, Hwang et al. (2007) concluded that patients are comfortable in the warm and humid conditions of the hospitals studied and seem insensitive to indoor thermal variations. This is counter to their own predictions using the PMV-PPD model and those of Khodakarami and Knight (2008). Regarding the staff, most of the studies concluded that the staff is not satisfied with the indoor conditions. Wang et al. (2012), Azizpour et al. (2013a, 2013b), and Yau and Chew (2009) conclude that occupants are adapted to the warm temperatures of the tropics and, therefore, their thermal neutrality is higher than predicted by the PMV-PPD model. However, even though the patients are satisfied with warmer temperatures, the majority preferred cooler temperatures rather than neutral. Contrasting the previously mentioned studies, Pourshaghaghy and Omidvari (2012) found a reasonably significant correlation between subjective votes from questionnaires and PMV in all wards and rooms, however, the effect of operable windows in maintaining comfortable room temperatures is not mentioned. It should be noted that Azizpour et al.'s (2013a, 2013b) focus was only on public, nonmedical areas, including kitchens, lobbies, and other areas not serving patients.

Except for Hwang et al. (2007), the analyses aggregate data from hospital zones with very dissimilar personal and environmental conditions. Pourshaghaghy and Omidvari (2012) differentiate between patients, staff, and visitors using only metabolic rates. Furthermore, these studies do not explain the assumptions about activity and clothing insulation levels. Hwang et al. (2007) does not describe the activity or clothing assumed in the models. On the subject of environmental variables, again, except for Hwang et al. (2007), only ranges or average values are provided for the whole period of study. The presence of operable windows is sometimes reported but is not considered in the analyses.

Results from subjective questionnaires indicate that patients seem to be thermally comfortable but that staff seem to be less comfortable with the hospital thermal environment. As expected, the PMV-PPD model is not always accurate in predicting the thermal comfort of patients. While the model considers a lower metabolism for patients, it does not account for their own behavioral adaptation and the level of care by the staff. Studies on the application of the PMV model raise the following concerns: in their analyses, most studies tend to aggregate highly different occupancy groups and wards; most studies do not provide a detailed description of the selection of the personal activity and clothing levels of occupants, and sometimes use aggregate values; most of these studies do not provide detailed analyses of the environmental variables or the levels of environmental control available to occupants.

In general, the studies conclude the comfort temperature for occupants in hospitals in the tropics is higher than prescribed through the PMV-PPD model. However, it is not clear if all the hospitals studied were fully air conditioned or have the possibility of opening windows in some surveyed areas. According to the adaptive theory, this would increase tolerance of higher indoor temperatures and preclude the use of the PMV model. Whenever possibilities for adaptation for a group of occupants are identified, these need to be considered in the analyses. From the literature, patients are more tolerant to varying indoor conditions, possibly owing in part to their enhanced possibilities for behavioral adaptation.

## Studies of Thermal Comfort in Operating Rooms

For reviews on thermal comfort in operating rooms (ORs), the reader is referred to Melhado et al. (2006) and Balaras et al. (2007). This paper discusses key findings to provide evidence of the validity of the PMV model predictions for surgical staff in the ORs and the challenges in applying the PMV-PPD model for the staff as well as for the patient.

Wyon et al. (1968) identified different thermal needs for surgeons, surgical assistants, nurses, and anesthetists: surgeons would be comfortable at conditions not exceeding 64.5°F (18°C), 50% rh, and 25 fpm (< 0.15 m/s) air speed; surgical assistants would prefer ambient temperatures 1°F (0.55°C) higher, and anesthetists would prefer higher temperatures of about 71°F (21.7°C). According to Wyon et al., the only way of reconciling these differences would seem to be for the anesthetists and other staff to wear warmer clothing. Mora et al. (2001) studied the ORs in Montreal General Hospital and concluded that surgeons tend to feel from "slightly warm" to "warm" and often experience regulatory sweating. Anesthetists and nurses, by contrast, experience a

**Table 2. Literature Review on Thermal Comfort in Hospitals**

| Reference | Country/ Climate | Study Season | Occupant Group | Research Methods O | Research Methods S | Research Methods T | Activity, met | Clothing, clo | Building / Department | Operation, approx. ranges | Findings |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Khodakarami and Knight (2008) | Iran/ various | August–September | P ✓ | — | — | ✓ | Awake: 0.82<br>Asleep: 0.70 | Uncovered: 0.49<br>Covered: 0.7–1.39 | Hospital: 14 patient rooms, general, and maternity | AC, windows operable,<br>$t_{air}$ : 72°F to 86°F (22°C to 30°C)<br>RH: < 60% | • Staff is too hot and patients are too cold (compared ISO 7730 and ASHRAE Standard 55).<br>• From PMV, patients are more sensitive due to low activity; varying clothing insulation makes conditions acceptable for most patients.<br>• Results are limited due to lack of surveys. |
| | | | W ✓ | | | | Various: 1.5 avg. | 0.88 | | | |
| | | | V — | — | — | — | — | — | | | |
| Pourshaghaghy and Omidvari (2012) | Iran/ Subtropical | Summer/ Winter | P ✓ | ✓ | ✓ | ✓ | 1.1 | Men:<br>0.9 winter<br>0.52 summer<br>Women:<br>1.1 winter<br>0,61 summer | Several wards, nurse stations, passageway, resting room | Except for surgery, no controlled air distribution is supplied. Operable windows and water coolers in rooms.<br>Winter:<br>$t_{air}$ : 63°F to 66°F (17°C to 19°C)<br>Summer:<br>$t_{air}$ : 77°F to 82°F (25°C to 28°C) | • Results are analyzed by wards. Data from subjective questionnaires seem to correlate well with PMV-PPD in all wards.<br>• The highest level of thermal dissatisfaction is reported in the surgery rooms, both in summer and winter.<br>• The study does not differentiate clothing levels between workers, patients, and visitors. |
| | | | W ✓ | ✓ | ✓ | ✓ | 1.9 – 2.0 – 2.3 | | | | |
| | | | V ✓ | ✓ | ✓ | ✓ | 1.5 | | | | |
| Hwang et al. (2007) | Taiwan/ hot-humid | Summer/ Winter | P ✓ | ✓ | ✓ | ✓ | — | — | Hospital: 83 medical and surgical wards | Winter:<br>$t_{air}$ : 66°F to 75°F (19°C to 24°C)<br>RH: 40% to 95%<br>Summer:<br>$t_{air}$ : 72°F to 81°F (22°C to 27°C)<br>RH: 45% to 90% | • Despite the high humidity, patients report neutral thermal sensation and higher acceptability than PMV-PPD (i.e., PMV-PPD overpredicts patients' thermal dissatisfaction).<br>• Large air temperature variations have little effect on the thermal sensations of patients. Physical strength significantly affects thermal requirements.<br>• Patients prefer warmer than neutral temperatures and tolerate much higher humidity as a result of adaptation to the climate of Taiwan. |
| | | | W — | — | — | — | — | — | | | |
| | | | V — | — | — | — | — | — | | | |
| Wang et. al. (2012) | Taiwan/ hot-humid | July and August | P, W ✓ | ✓ | ✓ | ✓ | 1.4 | 0.53 | Hospital: several medical wards | $t_{air}$: 72°F to 81°F (22°C to 27°C)<br>RH: 50% to 60% | • Patients are limited to those in waiting areas.<br>• Patients and staff are grouped. Staff and waiting patients prefer cooler environments than the existing ones.<br>• PMV is parallel to thermal sensation vote (TSV) at various operative temperatures but shifted about +0.5, indicating that occupants feel cooler than predicted. |
| | | | V — | — | — | — | — | — | | | |
| Azizpour et al. (2013a, 2013b) | Malaysia/ hot-humid | May and June, February | P — | — | — | — | — | — | Hospital: praying, corridor, kitchen, lobby, and offices | $t_{air}$ : (72°F to 82°F) 22°C to 28°C<br>ET*: 18°C to 26°C (64°F to 79°F) | • Strong correlation between actual TSV and PMV. However, 0 TSV corresponds to +0.7 PMV, indicating that the occupants' neutral temperature is higher than predicted.<br>• Occupants feel neutral in warmer environments (long-term climate adaptation) but prefer cooler temperatures than neutral (short-term thermal history). |
| | | | W ✓ | ✓ | ✓ | ✓ | Office: 1.2,<br>Praying: 1.3,<br>Lobby: 1.5<br>Kitchen: 2 | 0.6 – 0.7 | | | |
| | | | V ✓ | | | | | | | | |
| Yau and Chew (2009) | Malaysia/ hot-humid | Summer | P — | — | — | — | — | — | 4 hospitals (private and public): several medical wards | $t_{air}$ : 66°F to 86°F (19°C to 30°C)<br>RH: 44% to 79% | • Most occupants reported cold discomfort.<br>• The study concludes that these hospitals fail to provide adequate thermal comfort to occupants.<br>• Furthermore, the actual mean vote (AMV) from surveys indicates a higher neutral air temperature of 77.5°F to 82.8°F (25.3ºC to 28.2ºC) compared to the PMV. |
| | | | W ✓ | ✓ | ✓ | ✓ | 1.0, 1.2, 1.6, 2.0, 3.0 | 0.74 average | | | |
| | | | V — | — | — | — | — | — | | | |

P: patient, W: worker or staff, V: visitor O: objective measurements, S: subjective questionnaires, T: theoretical calculations (e.g. PMV-PPD), ET*: Effective Temperature index.

thermal sensation of "slightly cool" to "cold." The results agree with Olesen and Bovenzi (1985), who reported preferable thermal conditions for anesthetists at 73°F to 75°F (23°C to 24°C), for nurses at 72°F to 76°F (22°C to 24.5°C) and for surgeons at 64°F to 66°F (18°C to 19°C). Mora et al. (2001) found discrepancies for surgeons between the PMV-PPD model and satisfaction scores from subjective questionnaires. These discrepancies were due to significant thermal asymmetries on surgeons due to surgical lights. Sweating by surgeons was visibly observed by Wyon et al. (1968) and reported on questionnaires by Mora et al. (2001). There was more sweating and the staff felt hotter when the "atmosphere" in the operating room was tense and when there were more frequent entries and exits into and out of the operating room (Wyon et al. 1968). Hart et al. (2011) state that most OR personnel find the temperatures required for patient normothermia uncomfortably warm and, thus, lower OR temperatures are the norm. They conclude that surgeons are particularly vulnerable to warm ORs because of the high level of stress during surgery and because they must wear multiple layers of clothing, including sterile gowns and lead aprons. Physicians and other staff may perspire into a surgical incision if the OR is not kept cool. Warm temperatures may also impair the performance of OR personnel by decreasing their alertness. Van Gaever et al. (2014) compared PMV thermal comfort predictions using a hypothetical OR under standard Dutch operating conditions, based on surveys from four Belgian hospitals. The results from the questionnaires reveal the same trend as predicted by the PMV model. Discrepancies are explained by local discomfort factors, which are neglected by the PMV model. However, local discomfort factors are accounted for separately by other models included in ASHRAE Standard 55 (ASHRAE 2017a).

Mazzacane et al. (2006) monitored the skin temperatures of the staff during surgeries to study the impact of clothing and the type of surgery performed on thermal comfort and thermal stress of the staff. Mazzacane et al. (2006) indicate that surgeons and assistants must wear non-transpiring paper overalls beneath plasticized overalls in addition to protective masks and caps. Then, if X-rays are needed during surgery, the second surgeon and the assistants must also wear lead overalls and lead thyroid collars and gloves. They conclude that surgeries with prostheses—such as femur fracture and reconstruction—are those in which the whole staff is subject to serious thermal stress. These are the longest operations with the greatest number of recorded infections. They also find that the higher thermal stress conditions depend on the type of clothing worn and its thermal resistance, with the most intense sweating conditions corresponding to the periods when the subjects wore lead overalls.

Anesthesia impairs thermoregulation; therefore, the patient's body temperature drops steadily with anesthesia (Hart et al. 2011). Morris (1971) studied 45 lightly anesthetized, paralyzed patients having intra-abdominal or extra-abdominal surgery. Significant linear correlations were found between the patients' internal temperatures and their OR temperatures at intervals of one, two, and three hours after induction of anesthesia. Morris classified OR by their effects on patients' core temperatures: 1) rooms below 70°F (21°C), in which all patients became hypothermic; 2) 70°F to 75°F (21°C to 24°C) rooms, in which 70% of the patients remained normothermic (i.e., activity of blood cells is not increased or depressed by the environmental temperature), and 30% became hypothermic; and 3) 75°F to 79°F (24°C to 26°C) rooms, in which all patients remained normothermic. Medical research on the risk of perioperative (preoperative, intraoperative, and postoperative) hypothermia on patients confirm that air temperature is the single most critical factor affecting patients' heat loss. In a multivariate linear regression analysis (De Brito et al. 2009), the various types of anesthesia, duration of anesthesia, body mass index, and OR temperature were directly associated with the mean body temperature of the subjects studied. Therefore, patient core temperature monitoring is a requirement for long surgical procedures. Evidence suggests that patient prewarming for a minimum of 30 min may reduce the risk of subsequent hypothermia (Hart et al. 2011) and significantly reduce the risk of preoperative anxiety in patients (Wagner et al. 2006).

In conclusion, research evidence demonstrates that despite the inherent complexities involved in the accurate prediction of thermal comfort for the staff in the OR, the PMV-PPD model is applicable to the surgical staff. In general, the research results are consistent, not only in the trends for each member of the staff but also in the ranges of temperatures that are required for the thermal comfort of each member. Discrepancies are explained by local discomfort factors, which can be accounted for separately, and by uncertainties in the input parameters. For the thermal comfort of the patient, however, further research is needed.

## General Thermal Comfort Studies on Patients in Hospitals

Hwang et al. (2007) conclude that physical strength significantly affects the thermal requirements for patients. Hashiguchi et al. (2005) conducted a field study on patients and staff in a hospital in Japan in winter. In general, the indoor humidity fluctuated between 25% and 45%. From surveys, the study concludes that most patients find the thermal environment comfortable, while the thermal environment is too hot and dry for staff members. However, a large percentage of patients were conscious of itchy skin and thirst. This study did not compare subjective responses and objective measurements with PMV predictions. Skoog et al. (2005) combined subjective questionnaires and objective measurements to assess the indoor environment in orthopedic wards during summer and winter in Sweden with most windows open in the patient rooms during the summer. The surveys report high thermal satisfaction for both patients and staff and perception of low air humidity in both summer and winter. Table 3 summarizes their findings.

In Table 3, the activity level (metabolic rate) of staff seems excessively high. This explains why the predicted operative temperature for comfort is so low compared to the optimal temperature reported in surveys. The authors explain the differences between results from surveys and predictions for patients as likely a result of patients being more forgiving with indoor climate because they expect a short stay in the hospital and being able to easily control their level of clothing. Thus, they accept warmer temperatures. For staff, the authors explain that their activities vary throughout the day. These factors are not reflected in the model results. The authors argue that even though the PMV model was not made for hospital environments, the method for analyzing the indoor climate works well in hospital wards. Another explanation for the largest discrepancies between the predicted and optimal operative temperatures between the PMV model and surveys for patients is that in the summer, if the building is not air conditioned, patients' comfort temperature is more attuned to the outdoor temperature. Following the adaptive theory, their comfort temperature is warmer, which is not reflected in the PMV-PPD model. The activity levels for staff seem excessively high, particularly in the summer, which results in lower comfort temperatures. The authors do not provide support to justify their assumptions on the personal comfort variables.

Verheyen et al. (2011) studied the thermal comfort of patients in various hospital wards in Belgium using subjective questionnaires and objective measurements. The authors sorted the analysis by department or ward to be able to differentiate the thermal needs of subgroups of patients with the intent to provide a first indication of the applicability of the PMV method for groups of patients according to the surgical recovery or medical treatment provided. For patients, the authors used a new PMV model developed by Lin and Deng (2008) for sleeping environments in the subtropics. The authors carefully selected patients' clothing and bedding and monitored metabolic rate for sleeping activity. According to the study, "the thermal environment of the health care facility is acceptable to 95% of the patients, despite of 29% of the thermal environments not complying with ASHRAE Standard 55-2013 design ranges of temperature and humidity."[2] The authors point out that this result could indicate that adaptation possibly allows broader regions of recommended environmental parameters. The study concludes the PMV model may adequately predict mean thermal sensation for most of the patient population of the wards except for the neurology ward (due to effects from impaired organs of vital importance to human thermosphysiology as pointed out by the authors). Therefore, the new PMV model for sleeping environments can be applied to the patient population. The effect of patients' health on thermal sensation and acceptability was tested by asking the patients to self-describe their health status. The results indicate that the actual mean vote (AMV) was consistently higher in all wards than the PMV. This suggests that "unhealthy" patients present a lower thermal-neutral temperature in comparison to healthy adults. However, the difference between reported AMV on unhealthy patients and the PMV for sleeping healthy adults was statistically insignificant.

## Thermal Confort Studies on Patients with Disabilities

For patients and people with disabilities, the nature of the disease and disability determines the thermal requirements. At the sensory (perception) level, patients suffering from paralysis due to spinal cord injuries, paraplegia, or tetraplegia, lose sensitivity of portions of the body, which affect thermal sensation (Attia and Engel 1983). At the physiological (response) level, they lack efficient vasoconstriction and/or vasodilation, and/or there is restricted shivering and sweating in insentient portions of the body (Attia and Engel 1983). At the physical level, patients with limited mobility suffer from restricted ability for behavioral adaptation by changing posture and clothing to maintain comfort (Parsons 2002). At the intellectual/cognitive level, patients with dementia show altered sensitivity to the environment and reduced intellectual ability to discern and communicate needs (Van Hoof et al. 2010). Children with

[2] Verheyen, J., N. Theys, L. Allonsius, and F. Descamps. 2011. Thermal comfort of patients: Objective and subjective measurements in patient rooms of a Belgian healthcare facility. *Building and Environment* 46(5):1203.

**Table 3. Study in Swedish Hospitals (Skoog et al. 2005)**

| Occupancy Group | Season | Clothing Insulation, clo | Metabolic Rate, met | Approx. RH | Optimal Operative Temperature for Comfort, Based on Surveys | Predicted Operative Temperature, Based on PMV |
|---|---|---|---|---|---|---|
| Patients | Summer | 0.52 | 1.1 | 45% | 72.3°F (22.4°C) | 77°F (25°C) |
| | Winter | 0.64 | 1.3 | 20% | 72.7°F (22.6°C) | 73°F (23°C) |
| Staff | Summer | 0.57 | 2.5 | 45% | 72.3°F (22.4°C) | 64°F (18°C) |
| | Winter | 0.61 | 2.0 | 20% | 72.7°F (22.6°C) | 68°F (20°C) |

combined physical and mental disabilities are observed to suffer from thermoregulatory disorders (Yoshida et al. 2000). Therefore, the risks of discomfort, overheating, overcooling, and hypothermia are higher for certain groups of patients and people with disabilities.

Hill et al. (2000) studied thermal comfort for patients with physical disabilities from the point of view of the staff caring for them. They report that of the types of the patient complaints received, the most common request was to be warmer, although the staff tended to want to be cooler. Many people with physical disabilities were affected both physically and mentally when they felt too warm or too cold. Over the years, there have been many studies by the medical community on patients with spinal cord injuries. Attia and Engel (1983) compared deviations of core temperatures of spinal cord patients versus nondisabled persons under varying indoor climate conditions and recorded subjective thermal sensations. The results agree with those of previous studies: patients with paraplegia or tetraplegia show lower core temperatures in the cold and higher core temperatures in the heat when compared against physically nondisabled patients. This is due to a lack of efficient vasoconstriction, vasodilation, and sweating in the insentient portion of the body. Finally, it has been observed arthritis and stroke patients tend to wear more clothing when compared with the nondisabled (Parsons 2002).

### Thermal Comfort Studies on Elder Patients

Aging populations in developed countries are motivating research on elder care centres. A common complaint among hospitalized elderly patients is discomfort related to the cool environment (Robinson and Benton 2002). Studies show that due to slow metabolism, older adults prefer a warmer environment (+3.6°F [+2°C]) than younger people (van Hoof and Hensen 2006). Hwang and Chen (2010), reported an optimum temperature above 77°F (25°C) for sedentary older adults in residential environments. Evidence indicates that warmed blankets are effective in reducing discomfort in elder patients (Robinson and Benton 2002). Mendes et al. (2015) conducted an indoor air quality and thermal comfort study on elderly care centers in Portugal. The study included objective measurements of thermal comfort, which were used to calculate PMV. The PMV index shows significant differences by season. In winter, the PMV index shows a "slightly cool" thermal sensation and higher thermal dissatisfaction which, according to the authors, may potentiate respiratory tract infections.

Van Hoof et al. (2010) conducted a review of thermal comfort in which they argue that people with dementia are known to have altered sensitivity to environmental conditions, and they propose a set of integrated design requirements for homes for older people with dementia. Furthermore, they tend to respond on a sensory level, rather than on an intellectual level, and behaviors may be exacerbated by inappropriate environments. Therefore, they are unable to communicate what makes them uncomfortable. The authors investigate several ethical issues such as autonomy versus benefice, intelligent systems versus cognitive abilities, and controls systems versus limitations to cognition. They also explore the role of technology and building systems. For example, environmental control technology at homes should look familiar, control should not be removed from the user, the user interaction should be kept to a minimum, and the user should be reassured. Findings regarding building systems include: automated blinds may be perceived as threatening, cold bathrooms should be avoided, room controls' usability is critical, delays in climate systems' responses are problematic, and radiant surfaces are favoured.

## DISCUSSION

In principle, previous studies demonstrate that thermal comfort models can be applied with caution to rooms that serve healthy patients and staff. However, the review uncovers important differences between occupant groups and subgroups in health care that require individual attention and bring into question the minimum 80% thermal satisfaction target prescribed by ASHRAE Standard 55 (2017a). For some of these groups and subgroups, 100% satisfaction should be the target. For most patients, this target can be achieved with local or personalized comfort solutions.

As revealed in the literature review, there is a lack of systematic research on thermal comfort in health care settings. There are few studies that focus on individual facilities, departments, and rooms. With a few exceptions in specialized areas, the occupancy diversity in health care settings is not adequately acknowledged in existing thermal comfort research. Many studies characterize occupancy groups generically, with little attention to individualities.

Considering activity and clothing levels, which are the personal factors affecting the body's thermal balance with the environment, there is a lack of data on metabolic rates and clothing insulation characteristics for the variety of activities and occupants in health care. For the medical staff, data are needed on the magnitude of the stepwise temperature and metabolic changes and the effects of these on thermal comfort, as well as the effect of body movement on increased air velocity and clothing insulation.

The general studies on thermal comfort in hospitals in the tropics present contradicting results on the applicability of the PMV-PPD thermal comfort model in hospitals. This is not surprising given the broad scope of the field studies (from several wards to several hospitals) and the wide range of uncontrolled factors affecting the data from the field. Nevertheless, the studies conclude that the comfort temperature for occupants in hospitals in the tropics is higher than prescribed through the PMV-PPD model by ASHRAE Standard 55 (2017a).

Operating rooms have been by far the most studied rooms for thermal comfort in hospitals. The studies show that the PMV-PPD model is applicable to OR staff, but care must be exercised to account for local discomfort due to possible thermal environmental asymmetries. The studies demonstrate two dissimilar groups of staff: those close to the patient and those at the perimeter. Each group has its own thermal comfort considerations. For example, aside from clothing and activity levels, the studies show that radiant thermal asymmetries may be a factor for discomfort in surgeons, and psychological factors such as mental stress appear to cause discomfort in surgeons. Considering patients, medical research indicates that the risk of perioperative hypothermia is mainly dependent on type and duration of anesthesia, body mass index, and OR temperature.

Considering general studies on patients in hospitals, evidence from the field studies in hospitals suggests that, regardless of the climate, most patients seem satisfied with the thermal environmental conditions provided by hospitals and, contrary to PMV-PPD predictions, show apparent reduced sensitivity to indoor environmental changes. The possible reasons given by the literature are that patients are cared for and therefore maintained "warm"; patients have lower thermal expectations due to the short stay in the hospital; patients have other, more important concerns than thermal comfort; and unlike staff, patients may adapt by using blankets, changing posture, or changing clothing. Psychological adaptive aspects need further research to answer the question: are the patients more tolerant to variable indoor conditions owing to perceived enhanced possibilities for thermal adaptation, short stay, and more pressing health concerns? The physiological adaptive aspects are implicitly considered by the PMV-PPD model through varying activity levels and clothing insulation, which begs the question, given the lack of data: are the personal thermal factors for the patient being properly assessed in field studies?

Research on thermal comfort for subgroups of patients, i.e., specialized types of patients, has focused mainly on two subgroups: patients with disabilities and elder patients. Addressing thermal comfort for patients with disabilities involves increased complexities consistent with the nature of the disability. Therefore, research on thermal comfort for these types of patients pertains more to domains of medical research. For elder patients, research evidence indicates that they tend to feel cold and therefore prefer warmer environments and also that warmed blankets are effective in reducing discomfort. The complexities in addressing thermal comfort for elder patients are directly related to their health conditions. Disabled elders and elders with dementia pose unique challenges.

## CONCLUSION

Health care facilities need to aim for satisfactory thermal comfort both for the medical staff to deliver patient care and for the patients' comfort. As this study illustrates, the complexities of assessing thermal comfort include concurrent and potentially conflicting thermal comfort factors for medical staff and patients in the same space, a patient's health and care, the level of activity and required clothing of medical staff, the transient nature of occupants, and the steady-state nature of the comfort models.

According to the literature reviewed, field studies show patients tend to be more accepting of the indoor conditions than predicted by the comfort models, older and weaker patients tend to prefer warmer temperatures, and in many cases patients have the option of adaptive measures such as adding gowning or bedding insulation. Determining what range of temperatures and humidity levels the HVAC system should maintain is a complex problem that challenges the use of the PMV-PPD thermal comfort model.

This study can be considered a first step in exposing the challenges to assess thermal comfort in health care facilities, aiming to enhance existing models and possibly develop new models and tools to adequately support thermal comfort design in health care.

## ACKNOWLEDGMENTS

This study is the result of collaborative work between members of ASHRAE Standing Standard and Project Committees 55 and 170. The authors are thankful to the members of both groups involved in the project for the input from many meetings and discussions that helped shape this paper. In particular, many thanks to Travis English and Paul Ninomura for initiating and leading the discussions and raising the importance of this topic.

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