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Research on the influence of indoor thermal environment and activity levels on thermal comfort in protective clothing

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A B S T R A C T
With the outbreak of infectious diseases such as Corona Virus Disease 2019, medical staff work intensively in isolated plots, medical disposable protective clothing (MDPC) has poor air condition and humidity permeability, which seriously reduces the thermal comfort of medical staff. In this paper, the effect of indoor thermal environment and activity levels on thermal comfort inside MDPC was studied by experiment. Five parts of the body were measured inside MDPC and the appropriate movements were chosen to simulate different levels of labor intensity. Meanwhile, physiological parameters and subjective thermal sensation were statistically analyzed. The results showed the influence range of different indoor temperatures on the temperature and humidity inside MDPC was about 1°C and 10%, respectively; it indicated that the environment inside MDPC could be improved by reducing indoor temperature, that is, a cross intelligent adjustment mode was proposed. The effect of labor intensity on the temperature inside MDPC was significantly less than that of humidity. Within 20 min, the humidity changes under moderate and heavy labor intensity were even more than 10%, and the subjective discomfort threshold of the subjects increased by nearly 50%. Furthermore, the maximum benefit could be obtained by concentrating cooling on back, forehead, chest and upper arm. Theoretical models of working time, labor intensity, and temperature and humidity inside MDPC under different indoor temperatures and different parts were given. In addition, acceptable regions inside MDPC which were approximately parallelogram in the enthalpy-humidity chart. These conclusions could be a reference for future thermal comfort inside MDPC research.

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1. Introduction

From 2019 to present, COVID-19 epidemic prevention and control campaign is fought [1,2], medical staff are required to wear medical disposable protective clothing (MDPC) when entering isolated plots [3–5]. Currently, MDPC already has good protective performance, but still has the disadvantages of poor breathability and moisture permeability. Wearing protective equipment for a long time can easily lead to physical discomfort and psychological anxiety [6–9], the sense of experience is very poor, which is harmful to the health of medical staff [10,11].

Therefore, it is necessary to evaluate and improve the thermal comfort inside MDPC, which is related to the health and work efficiency of medical staff, and it will create a more comfortable environment for medical staff [12].

The research on the thermal comfort of MDPC is still focused on the thermal-wet comfort of fabric. The Technical Requirements for Medical Disposable Protection numbered GB19082-2009 has stipulated that the humidity permeability of MDPC should not be less than 2500 g/(m²·d) [7]. Bartkowiak et al. [13] put forward the viewpoint of sensory comfort by choosing the fabric of reference clothing for ergonomics test of MDPC. Jiang et al. [14] conducted a humidity permeability test on the comfort of several different MDPC fabrics, the research showed that the humidity permeability of various coated materials was far lower than that level. It was suggested that the humidity permeability of the fourth and fifth grade materials could be increased to 4500 g/(m²·d). In short, the
poor air condition and humidity permeability of MDPC affected the thermal comfort requirements and work efficiency of medical staff [15,16]. Therefore, it is necessary to carry out in-depth study of this part.

In addition, the use of MDPC could cause a series of physiological and psychological discomfort. Studies showed that wearing MDPC during moderate physical exercise reduced the upright tolerance greatly, and there were important cardiovascular changes in participants who had good orthostatic tolerance before [17]. Various adverse skin reactions may occur among medical staff [18]. Thermal environment parameters and clothing insulation will affect the thermal physiological comfort [19,20]. So, there is a great need to improve the thermal comfort of MDPC.

Many scholars have studied the improvement of MDPC from different aspects [21–24]. Lin et al. [25] proposed a new MDPC material with a super absorbent layer, which will improve hygroscopic properties and could be used in certain parts of MDPC. Wang et al. [26] analyzed the application status of antibacterial MDPC from the aspect of antibacterial materials, process technology and technological intelligence. Wang et al. [27] studied the thermal comfort of four typical MDPC by using a sweating thermal manikin, the results showed that sweat output was small at light labor intensity, which did not affect the physiological activities of the human body; at heavy labor intensity, sweat output increased rapidly to a large extent and was difficult to discharge, which indicated that it was not easy to carry out heavy labor intensity when wearing MDPC. However, the thermal comfort index had not been specifically quantified, which partly failed to provide scientific theoretical reference for MDPC designers.

In summary, the current research methods on the thermal comfort of MDPC mainly include fabrics testing [28], thermal manikin [29] and human wear trial experiments [30]. However, the existing conclusions on the thermal comfort of MDPC lack practical significance and theoretical reference. The thermal comfort with MDPC was affected by various factors [31–33]. Moreover, related literature mostly adopted computer simulation or thermal manikin experiments, which lacked subjective feelings and ignored the influence of human real physiological and psychological factors, so the research in this field needed to be supplemented and improved.

In this study, the traditional research method of thermal comfort will be adopted, voted subjectively by human experiment. The participants were asked to vote for thermal sensation in accordance with the way medical staff in isolated plots wear, so as to study the thermal comfort of MDPC. The research results could provide quantitative data and theoretical model for the development, improvement and selection of MDPC, improve the thermal comfort of MDPC and the efficiency of medical staff, thereby rescuing more patients.

2. Material and methods

2.1. Experimental conditions

The experiment was conducted from December 2nd, 2020 to December 7th, 2020, and the change in outdoor temperature was relatively small, in the range of 0–4 °C. The available space of the experimental area was 6.5 m × 6.5 m × 3.4 m. Fig. 1 shows the configuration of the chamber and some real experimental scenes. The material of MDPC in this study was PP + PE coated nonwoven fabric, and other performance indicators meet the requirements of GB19082-2009 (Table 1).

14 participants in good health were recruited for this study. They were divided into 7 groups, with two participants in each group to simulate MDPC group and ordinary clothing group (OC group), respectively, and then MDPC group and OC group were interchanged, so a total of 14 groups were obtained. In addition, thermal environment parameters in each group of experimental chamber were basically stable according to the actual measurement, and the average temperature of the entire test period was taken as a reference. According to the indoor design temperature, the average temperatures could be divided into 19 °C and 21 °C. As the temperature and humidity inside MDPC were relatively high, a group of average temperature of 17 °C was also tested as poor air condition and humidity permeability of MDPC affected the thermal comfort requirements and work efficiency of medical staff [15,16]. Therefore, it is necessary to carry out in-depth study of this part.

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2.2. Research methods

2.2.1. Experimental scheme and measured data

The measuring points inside MDPC were arranged according to the algorithm of weighted average skin temperature [34–36] combined with reference to various parts of the human body’s sweat distribution. Considering comprehensively, the five-point weighting method was selected in this paper according to Eq. (1), includes the body parts of the forehead, chest, back, upper arm and thigh. It was not only arranged in the parts where the human body temperature changed sensitively and has a large amount of sweating as much as possible, but also reduced the influence of measuring points arrangement on the thermal sensation of subjects to the greatest extent. In order to minimize the weight of the instrument, no bilateral measurements were performed at the thigh and upper arm positions, and only the right side with a large amount of activity was selected as a reference.

\[
T = 0.067T_F + 0.34T_C + 0.33T_B + 0.14T_U + 0.13T_T \tag{1}
\]

where \(T\) is mean temperature inside MDPC; \(T_F\) is the temperature of the forehead; \(T_C\) is the temperature of the chest; \(T_B\) is the temperature of the back; \(T_U\) is the temperature of the upper arm; \(T_T\) is the temperature of the thigh.

During the experiment, MDPC and PPE should be worn by MDPC group, and were asked to cooperate with the experimental operators to attach HOBO data loggers to the middle position of the chest, back, right thigh, right upper arm and forehead of the isolation clothing. The instruments were in good condition and data were recorded once in five minutes. Each experiment was lasted about two hours, divided into four stages of different labor intensity, each stage lasted 20 min. Therefore, 16 sets of data were obtained in each experiment, and a total of 224 sets of data were obtained from all experiments. Fig. 2 shows the layout of the measuring points. OC group wore ordinary disposable medicine masks and remained within the range of light labor intensity at all times.

All participants wore standard clothes (underclothes, long-sleeved shirt, trousers, socks and sneakers), with a clothing thermal resistance of 1.0 clo. According to the MDPC thermal manikin test in the literature [37], the clothing thermal resistance of MDPC group is about 3.0 clo [38]. The experimental procedure and the experimental site are shown in Figs. 3 and 4, respectively. The instruments used in this experiment were shown in Table 3.

2.2.2. Subject and questionnaire

Thermal sensation vote (TSV), humidity sensation vote (HSV), thermal comfort vote (TCV) and acceptable degree (AD) were obtained by questionnaires for the OC and MDPC group. The general international scale was used by the OC group. The MDPC group had made some corrections to the TCV and HSV due to the extensive range of thermal and humidity variation in the clothing, in which HSV added information about the dampness of the skin. The questionnaire added information about the body condition, such as fatigue, nausea, chest distress, dry eyes, dizziness and headache, and also included the most desired body parts for improvement. Fig. 5 shows the scales of partial questions in questionnaire.

![Fig. 1. The configuration of the chamber and some real experimental scenes.](image)

### Table 1

The performance indicators of MDPC.

| Indicators                             | Requirement                      |
|---------------------------------------|----------------------------------|
| Water resistance                      | ≥1.67 kPa (17 cm H₂O)            |
| Water vapor permeability              | ≥2500 g/(m²·d)                   |
| Resistance to synthetic blood penetrability | ≥1.75 kPa                     |
| Filtration efficiency                 | ≥70 %                            |

### Table 2

The information and group settings of the participants.

| Group number | Indoor average temperature (°C) | Average humidity (%) | Participant serial number | Gender | Age  | Height (cm) | Body weight (kg) |
|--------------|---------------------------------|----------------------|---------------------------|--------|------|-------------|------------------|
| I            | 17                              | 18                   | 1                         | Female | 24   | 160         | 47               |
|              |                                 |                      | 2                         | Male   | 24   | 180         | 70               |
| II           | 19                              | 20                   | 3                         | Male   | 26   | 178         | 67               |
|              |                                 |                      | 4                         | Female | 23   | 163         | 54               |
| III          | 19                              | 20                   | 5                         | Male   | 25   | 178         | 74               |
|              |                                 |                      | 6                         | Female | 24   | 168         | 55,6             |
| IV           | 19                              | 20                   | 7                         | Male   | 23   | 181         | 80               |
|              |                                 |                      | 8                         | Male   | 22   | 172         | 70               |
| V            | 21                              | 20                   | 9                         | Male   | 25   | 180         | 70               |
|              |                                 |                      | 10                        | Male   | 24   | 175         | 71               |
| VI           | 21                              | 20                   | 11                        | Female | 25   | 159         | 47               |
|              |                                 |                      | 12                        | Male   | 26   | 182         | 82               |
| VII          | 21                              | 20                   | 13                        | Female | 25   | 162         | 53               |
|              |                                 |                      | 14                        | Male   | 24   | 176         | 65               |
2.3. Multifactor analysis of variance test

The data in this manuscript were analyzed by multifactor variance analysis [39], that is, under different indoor temperatures (17 °C, 19 °C, 21 °C), different parts (forehead, chest, back, thigh, upper arm), different labor intensity (sitting silently, light labor, moderate labor, heavy labor), the significance test of the temperature and humidity inside MDPC was carried out. Tables 4 and 5 were the test results of variance analysis.

According to the test results of variance analysis, these data have significant differences, and the experimental results are meaningful.

3. Results and discussion

3.1. Effect of indoor temperature on thermal comfort of MDPC

It can be seen from Fig. 6 that as the indoor temperature \(T_{\text{indoor}}\) increased, the temperature and humidity inside MDPC \(T_{\text{MDPC}}\) and \(H_{\text{MDPC}}\) also increased significantly. Under different indoor temperatures, the temperature inside MDPC changed at about 2 °C throughout the process, and the average temperature at high temperature (21 °C) was about 1 °C higher than that at low temperature (19 °C). The humidity inside MDPC changed obviously with the indoor temperature, and changed about 30 % during the process. With increased of indoor temperature, the humidity inside MDPC increased significantly, and the average humidity at high temperatures was about 10 % higher than at low temperatures. Therefore, indoor temperature had a greater impact on the humidity inside MDPC.

In summary, it could be found that the most important factors affecting the thermal comfort of medical staff when wearing MDPC in this experiment were the indoor temperature and the labor intensity.

When the average indoor temperature was 17 °C, the average temperature inside MDPC could be 0.5–2 °C lower than the indoor design temperature, of which 1–2.5 °C lower under moderate and heavy labor intensity. The average humidity inside MDPC could be 6–7 % lower than at the indoor design temperature, and could be reduced by 11–21 % under moderate and heavy labor intensity. It can be seen that the low temperature environment reduced the temperature and humidity inside MDPC, but the improvement was the most obvious only under moderate and heavy labor intensity, but it was not significant under sitting silently and light labor intensity.

According to changes in working time and labor intensity, the variation formula of temperature and humidity inside MDPC under different indoor temperatures was fitted. The formulas were shown in Eqs. (2) and (3), the corresponding coefficients were shown in Table 6.
Table 3  
Measurement instruments of this experiment.

| Instruments                        | Type                | Range                  | Precision                                      | Measurement                                      | Response time |
|-----------------------------------|---------------------|------------------------|------------------------------------------------|------------------------------------------------|--------------|
| Multifunction measuring           | Testo 480           | T: -20 to 70 °C, RH: 0–100 % | T: ±0.5 °C, RH: ±(1.8 % RH + 0.7 % measured value) | Temperature, humidity (indoor environment)       | 0.5 s        |
| instruments                       | HOBO data loggers   | UX100-003              | T: -20 to 70 °C, RH: 0–100 %                    | Temperature, humidity (environment inside MDPC)  | T: 4 min     |
| Electronic sphygmomanometer       | OMRON HEM-7200      | HR: 40–180 bpm, BP: 0–299 mmHg | HR: ±3 bpm, BP: ±3 mmHg                         | Heart rate, blood pressure                       | ~            |

Fig. 4. The experimental site (a) sitting silently; (b) light labor; (c) moderate labor; (d) heavy labor.

Fig. 5. The scales of partial questions in questionnaire.
Table 4
The inter-subject effect test of the temperature inside MDPC.

| Source               | Type III sum of squares | Degree of freedom | Mean square | F       | Significance | Eta-squared | Noncentrality parameter |
|----------------------|-------------------------|-------------------|-------------|---------|--------------|-------------|-------------------------|
| Modified model       | 431.149a                | 59                | 7.308       | 5.444   | 0.00         | 0.593       | 321.179                 |
| Intercept            | 175515.6                | 1                 | 175515.7    | 30748.3 | 0.00         | 0.998       | 10748.3                |
| Temperature          | 104.36                  | 2                 | 52.18       | 38.871  | 0.00         | 0.261       | 77.742                 |
| Parts                | 185.667                 | 4                 | 46.417      | 34.577  | 0.00         | 0.386       | 138.31                 |
| Labor intensity      | 61.867                  | 3                 | 20.622      | 15.362  | 0.00         | 0.173       | 46.087                 |
| Temperature * Parts  | 32.632                  | 8                 | 4.079       | 3.039   | 0.00         | 0.01        | 24.309                 |
| Temperature * Labor intensity | 4.306 | 6    | 0.718      | 0.535   | 0.014       | 0.014       | 3.208                  |
| Parts * Labor intensity | 38.59                | 12                | 3.216       | 2.396   | 0.006        | 0.116       | 28.747                 |
| Error                | 295.327                 | 220               | 1.342       |         |              |             |                         |
| Total                | 230914.142              | 280               |             |         |              |             |                         |
| Total after correction| 726.476                | 279               |             |         |              |             |                         |

Table 5
The inter-subject effect test of the humidity inside MDPC.

| Source               | Type III sum of squares | Degree of freedom | Mean square | F       | Significance | Eta-squared | Noncentrality parameter |
|----------------------|-------------------------|-------------------|-------------|---------|--------------|-------------|-------------------------|
| Modified model       | 70836.882a              | 59                | 1200.625    | 8.288   | 0.00         | 0.69        | 488.967                 |
| Intercept            | 425558.2                | 1                 | 425558.2    | 2937.511| 0.00         | 0.93        | 2937.511                |
| Temperature          | 25658.68                | 2                 | 12829.34    | 88.557  | 0.00         | 0.446       | 177.115                 |
| Parts                | 5554.367                | 4                 | 1388.592    | 9.585   | 0.00         | 0.148       | 15.465                  |
| Labor intensity      | 19530.99                | 3                 | 6510.331    | 44.939  | 0.00         | 0.38        | 134.817                 |
| Temperature * Parts  | 2240.349                | 8                 | 280.044     | 1.933   | 0.056        | 0.066       | 12.18                   |
| Temperature * Labor intensity | 1764.572 | 6    | 294.095    | 2.016   | 0.052        | 0.052       | 12.18                   |
| Parts * Labor intensity | 1315.175              | 12                | 109.598     | 0.757   | 0.04         | 0.04        | 9.078                   |
| Error                | 31871.48                | 220               | 144.87      |         |              |             |                         |
| Total                | 731718.1                | 280               |             |         |              |             |                         |
| Total after correction| 102708.4               | 279               |             |         |              |             |                         |

Fig. 6. The changes of temperature and humidity inside MDPC under different indoor temperatures.

Table 6
The coefficients of temperature and humidity inside MDPC under different indoor temperatures.

|        | \(T_{\text{indoor}} = 17 \, ^\circ\text{C}\) | \(T_{\text{indoor}} = 19 \, ^\circ\text{C}\) | \(T_{\text{indoor}} = 21 \, ^\circ\text{C}\) |
|--------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| \(a_1\) | \(-64.83468\)                               | \(212.62181\)                                | \(568.61165\)                                |
| \(b_1\) | \(3.0410203\)                                | \(-5.1279404\)                               | \(10.377677\)                                |
| \(c_1\) | \(233.99966\)                                | \(-563.36475\)                               | \(568.61165\)                                |
| \(d_1\) | \(-0.033795194\)                             | \(0.046541986\)                              | \(-199.57073\)                               |
| \(e_1\) | \(-199.57073\)                               | \(249.82117\)                                | \(568.61165\)                                |
| \(f_1\) | \(-4.8993187\)                               | \(5.1586015\)                                | \(10.377677\)                                |
| \(g_1\) | \(0.0001279354\)                             | \(-6.497319165\)                             | \(-4.8993187\)                               |
| \(h_1\) | \(54.52771\)                                 | \(-81.270778\)                               | \(-6.497319165\)                             |
| \(i_1\) | \(2.1185214\)                                | \(5.1586015\)                                | \(-4.8993187\)                               |
| \(j_1\) | \(0.024283654\)                              | \(-0.047688501\)                             | \(-6.497319165\)                             |
| \(R^2\) | \(0.9957113\)                                | \(0.98494782\)                               | \(0.9957113\)                                |
|        | \(a_2\)                                      | \(231.18613\)                                | \(231.18613\)                                |
|        | \(b_2\)                                      | \(-2.0163622\)                               | \(-2.0163622\)                               |
|        | \(c_2\)                                      | \(-693.77543\)                               | \(-693.77543\)                               |
|        | \(d_2\)                                      | \(-0.024759153\)                             | \(-0.024759153\)                             |
|        | \(e_2\)                                      | \(777.24819\)                                | \(777.24819\)                                |
|        | \(f_2\)                                      | \(5.8702194\)                                | \(5.8702194\)                                |
|        | \(g_2\)                                      | \(0.0003026565\)                             | \(0.0003026565\)                             |
|        | \(h_2\)                                      | \(277.87497\)                                | \(277.87497\)                                |
|        | \(i_2\)                                      | \(-4.1268122\)                               | \(-4.1268122\)                               |
|        | \(j_2\)                                      | \(0.022816148\)                              | \(0.022816148\)                              |
|        | \(R^2\)                                      | \(0.99494905\)                               | \(0.99494905\)                               |

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T_{\text{MDPC}} = a_1 + b_1 t + c_1/M_R + d_1 t^2 + e_1/M_R^2 + f_1 t/M_R + g_1 t^3 + h_1/M_R^3 + i_1 t/M_R^2 + j_1 t^2/M_R^4

H_{\text{MDPC}} = a_2 + b_2 t + c_2/M_R + d_2 t^2 + e_2/M_R^2 + f_2 t/M_R + g_2 t^3 + h_2/M_R^3 + i_2 t/M_R^2 + j_2 t^2/M_R^4

As the experiment requires OC group to ensure health as far as possible do not add or subtract clothing. Fig. 7 showed that the OC group was in a just acceptable state in the first 70 min, and then it felt from slightly cool to cool. People can achieve a comfortable state by decreasing clothing in a slightly cool state. The MDPC group was just acceptable in the first 70 min at 17 °C, and then it is possible do not add or subtract clothing. Fig. 7 showed that the OC group was in a just acceptable state in the first 70 min, and then it felt from slightly cool to cool. People can achieve a comfortable state by decreasing clothing in a slightly cool state. The MDPC group was just acceptable in the first 70 min at 17 °C, and the thermal and humidity sensation were significantly reduced even under heavy labor intensity.

After 70 min, the TSV of MDPC group reached hot, and the HSV also began to feel humid from the original neutral, and then remained unchanged. In the first 10 min of the beginning of heavy labor intensity, the amount of exercise increased, the human body sweated a lot, and the high tightness of MDPC, the sweat could not be discharged in time, so that the humidity inside MDPC increased rapidly, and the TSV and HSV of the human body increased rapidly. 10 min later, although the human body still continues to sweat, the humidity inside MDPC has reached a certain degree, and it is still within the acceptable range of the human body (if it is clearly acceptable, the experiment will be stopped), so it has little effect on the TSV and HSV of the human body, showing no obvious change and temporarily stabilizing state. It can be predicted that if the long-term continues in heavy labor intensity, the TSV and HSV reach the extreme, which has an impact on the sweat glands of the human body. It may even lead to shock, causing harm to human health, it is necessary to shift or change MDPC. The OC group after 70 min of the experiment, due to in a low temperature for a long time, the TSV and HSV were reduced, and the original neutral began to develop to cold, which also caused discomfort for the OC group. By comprehensive analysis, both OC and MDPC groups can reach a relatively comfortable state within the first 70 min in the low temperature environment.

Therefore, it indicated that the environment inside MDPC could be improved by reducing indoor environmental condition. In order to achieve the relative thermal comfort of the two, it was recommended that hospital buildings should reduce indoor temperature to 17 °C in places where only for medical staff who wear MDPC, especially under the moderate and heavy labor intensity, to create a better working environment; In the places where MDPC group and OC group exist at the same time, cross-regulation at 19 °C and 17 °C is adopted, to improve the acceptability of medical staff and avoid the cold feeling of others.

### 3.2. Effect of activity intensity on thermal comfort of MDPC

Since relative humidity is a comprehensive investigation value of temperature and moisture content, it is not easy to judge directly. Fig. 8 shows the change in internal humidity ratio of MDPC with time under different indoor temperatures. It could be seen that the humidity ratio was basically stable under sitting silently and light labor intensity. Under moderate and heavy labor intensity, the humidity ratio increased significantly, and increased by 3 g/kg and 4 g/kg within 20 min, respectively, and the average humidity ratio under heavy labor intensity was about 5 g/kg higher than that under moderate labor intensity. However, when the indoor temperature was 17 °C, the average humidity ratio under heavy labor intensity was only about 2 g/kg higher than that under moderate labor intensity, and was also 5–8 g/kg lower than that under other temperatures. It can still be explained that reducing indoor temperature can significantly improve the thermal comfort of MDPC clothing.

In addition, it can be seen from Fig. 6 that the temperature inside MDPC increased continuously while sitting silently at different indoor temperatures. Because there was no movement and...
poor heat permeability of MDPC, heat could not be dissipated, resulting in a continuous rise in the temperature of the microenvironment inside MDPC. About 15 min later, the temperature inside MDPC gradually stabilized. It also showed that people need a period of adaptation after wearing high airtightness MDPC. After 30 min, starting from light labor intensity, the temperature decreased partially of the process. For clothing reasons, MDPC was often too large for most people, the movement process would be brought about a breeze speed, and the slight humidity caused by sweating can also play a cooling role, so the temperature inside MDPC did not always rise. Therefore, in light labor, even moderate labor intensity (in the low temperature environment), the temperature inside MDPC was in a state of fluctuation or even decline. It showed that the temperature inside MDPC was reduced by maintaining a slight amount of exercise, which was beneficial to the thermal comfort of MDPC.

For the humidity inside MDPC, the average humidity inside MDPC was 35–45 %, 33–46 %, 37–56 % and 62–66 % under sitting silently, light, moderate and heavy labor intensity, respectively. The average humidity under moderate labor intensity was about 4–7 % higher than that under light labor intensity, and the average humidity under heavy labor intensity was about 13–24 % higher than under moderate labor intensity. Humidity rises sharply at moderate and heavy labor intensity. The maximum humidity inside MDPC reached more than 70 %, which occurred at the end of heavy labor intensity.

Fig. 9 shows the subjective thermal sensation changes of MDPC group at 19 °C and 21 °C. At high temperatures, TSV, HSV and TCV increased significantly, so discomfort threshold increased. It can also be seen that TSV and HSV did not change much in sitting silently and light labor stages, and basically the subjective feeling was acceptable. TCV showed slightly discomfort. But the subjective thermal sensation rapidly increased to the uncomfortable direction under moderate and heavy labor intensity, and the thermal comfort of the subjects decreased by nearly 50 %.

In Summary, the labor intensity has little effect on the temperature under moderate and heavy labor intensity. From Figs. 10 and 11, the three parts of the time, so the upper arm temperature was higher than the thigh. So the maximum benefit could be obtained by concentrating cooling on back, forehead, chest and upper arm.

Under different indoor design temperatures, the increasing extent of humidity was particularly pronounced under moderate and heavy labor intensity. From Figs. 10 and 11, The three parts with the highest humidity were the chest, back and upper arm, and the degree of sensitivity was upper arm > back > chest, and the humidity increased by about 30 % throughout the experiment at both low and high temperatures. Humidity in the thigh and forehead both increased by approximately 25 %. Combined Fig. 12 shows the humidity distribution, therefore, the degree of sensitivity of each part for humidity was: upper arm > back > chest > thigh > forehead. It could be found that the indoor temperature had a great influence on the humidity inside MDPC. MDPC has high evaporative resistance, when the humidity was high, sweat evaporation was not smooth, accumulated on the skin surface, produced adhesion, and with a feeling of chest distress, greatly reduced the comfort of human body.

The data above 50 % in the temperature and humidity of each part in Fig. 12 belong to the range of light to moderate labor intensity. The upper borderline of each part under different indoor design temperatures was higher and belonged to the range of heavy labor intensity, especially in the upper arm, back and chest. In the sitting silently stage, the temperature increased significantly in the first five minutes due to the adaptation of wearing MDPC.
and the first recorded temperature was easy to show an abnormal value. The long duration of heavy labor intensity led to a large amount of sweating and a sharp increase in humidity, the humidity inside MDPC showed abnormal value.

In summary, the temperature and humidity sensitivity of different body parts was different. Therefore, when improving measures were considered, such as adding phase change material, according to the adjustment of indoor temperature, different doses in different body parts were adopted, which was more conducive to improving the overall thermal comfort of medical staff.

According to the above changes of temperature and humidity inside MDPC in different parts, the relationship between working time, labor intensity, temperature and humidity inside MDPC were obtained by fitting formula. The formulas were shown in Eqs. (4)–(7), the corresponding coefficients were shown in Tables 7–10.
The coefficients of humidity variation inside MDPC in different parts ($T_{\text{indoor}} = 19^\circ \text{C}$).

| $a_1$ | 21.894622 | 22.271059 | 21.559278 | 22.301083 | 25.071392 |
| $b_1$ | 0.1252829 | 0.3444697 | -0.364472 | -0.011639 | 0.5135249 |
| $c_1$ | 0.2025273 | -6.410415 | 6.8641699 | 2.1512775 | -6.382624 |
| $d_1$ | 0.001909 | 0.0121069 | -0.004652 | 0.0028468 | 0.0044792 |
| $e_1$ | 1.4911542 | 11.256047 | -5.722584 | 0.613038 | 9.0518446 |
| $f_1$ | -0.152353 | -0.807482 | 0.3040293 | -0.140255 | -0.641885 |
| $g_1$ | 0.000215 | 0.0003642 | 0.0001398 | 0.0002466 | 0.0002629 |
| $h_1$ | -3.22665 | -6.476665 | -0.574788 | -3.257943 | -4.003426 |
| $i_1$ | 0.3938389 | 0.7250671 | 0.1472401 | 0.4254209 | 0.4501761 |
| $j_1$ | -0.016129 | -0.02734 | -0.008284 | -0.017651 | -0.017058 |
| $R^2$ | 0.996981 | 0.98971 | 0.976101 | 0.9718011 | 0.9654385 |

The coefficients of temperature variation inside MDPC in different parts ($T_{\text{indoor}} = 19^\circ \text{C}$).

| $a_1$ | 22.492288 | 33.71612 | 34.679808 | 38.927059 | 30.818555 |
| $b_1$ | 0.062702469 | -0.6972799 | -0.2439559 | -1.0852717 | -1.0143874 |
| $c_1$ | -0.0061608072 | 0.053061359 | 0.295001199 | 0.0861616 | 0.08098888 |
| $d_1$ | -0.0044723152 | -0.0017968149 | -0.001350154 | -0.0027255375 | -0.0025693772 |
| $e_1$ | 1.2360341e-05 | 2.5948441e-05 | 2.129893e-05 | 3.6971124e-05 | 3.0412935e-05 |
| $f_1$ | -7.4506653e-08 | -1.2192886e-07 | -1.209662e-07 | -1.6844342e-07 | -1.258313e-07 |
| $g_1$ | 6.7204813 | -0.3335795 | -2.763256 | -7.8999219 | 1.8876468 |
| $h_1$ | -2.3967952 | -0.72026156 | -0.43483296 | 1.1059043 | -0.60738748 |
| $R^2$ | 0.99767742 | 0.9990336 | 0.99712214 | 0.99928371 | 0.99020891 |

The coefficients of humidity variation inside MDPC in different parts ($T_{\text{indoor}} = 21^\circ \text{C}$).

| $a_1$ | 24.980096 | 27.429645 | 28.138964 | 28.934617 | 27.566271 |
| $b_1$ | 0.26790578 | 0.20790023 | 0.2096667 | 0.4123078 | 0.17041878 |
| $c_1$ | -0.0064660087 | -0.0078300015 | -0.008389609 | -0.0047022739 | -0.0041052811 |
| $d_1$ | 5.958382e-05 | 0.0001394584 | 0.0001550348 | 7.143581e-05 | 3.7117722e-05 |
| $e_1$ | -3.8117929e-08 | -1.2625912e-06 | -1.3050295e-06 | -5.4800163e-07 | -1.7560124e-07 |
| $f_1$ | -1.284758e-09 | 4.3959482e-09 | 4.1675659e-09 | 1.8201377e-09 | 5.8962177e-10 |
| $g_1$ | 0.6840714 | -0.51724432 | 0.28515297 | -1.0191541 | -1.1801741 |
| $h_1$ | -0.18862588 | 0.17552427 | -0.668436241 | 0.23423716 | 0.3063328 |
| $R^2$ | 0.99655968 | 0.97380535 | 0.99195701 | 0.96616885 | 0.97703613 |

The coefficients of temperature variation inside MDPC in different parts ($T_{\text{indoor}} = 21^\circ \text{C}$).

| $a_1$ | 22.797773 | 48.15648 | 21.797949 | 46.714214 | 34.343028 |
| $b_1$ | -2.544726 | 0.00021948376 | -1.360057 | -1.8246277 | -0.13677019 |
| $c_1$ | 65.801873 | 1.4488651 | 72.426707 | 36.072185 | 2.1301069 |
| $d_1$ | 0.053457877 | 0.079410798 | 0.021345543 | 0.014192674 | 0.0061577188 |
| $e_1$ | -17.296053 | 37.914641 | -29.975617 | -23.485197 | 33.488948 |
| $f_1$ | -0.44855316 | -3.4804012 | 0.16656448 | 0.9301683 | -2.9594664 |
| $g_1$ | 0.002143363 | 0.0016590268 | 0.00067480817 | 0.0002108041 | 0.0001982632 |
| $h_1$ | -31.14386 | -36.324925 | -10.122018 | -6.5528934 | -3.1993335 |
| $i_1$ | 4.176709 | 4.0823941 | 1.6047946 | 0.89911713 | 3.5764538 |
| $j_1$ | -0.17211263 | -0.14163765 | -0.06218291 | -0.032597969 | -0.12770194 |
| $R^2$ | 0.99569945 | 0.998624 | 0.99858889 | 0.99675202 | 0.99652868 |

3.4. Physiological parameters

As can be seen from Figs. 13 and 14, the effect of labor intensity on blood pressure (BP) was not significant, the pressure difference remained basically stable, while the heart rate (HR) of participants changed more significantly. When the labor intensity increased, especially in the heavy labor intensity, the heart rate values in the MDPC group increased significantly, by about 12% at low temperature and 21% at high temperature compared to the moderate labor intensity. The blood pressure and heart rate of the OC group
were maintained in a stable range. The extra weight of MDPC increased the burden on human body, increased heat production and accelerated blood circulation, which increased heart load and led to a high heart rate. The normal heart rate of an ordinary person was about 60–100 bpm, while it could be as high as about 110 bpm under heavy labor intensity. It may cause cerebral hypoxia to continue in this state, resulting in physical reactions such as vomit and nausea in the participants.

Moreover, the higher the labor intensity was, the worse the physical condition was, and the types of physical discomfort were also increased. The high temperature was more serious than low temperature. From Fig. 15, when the average indoor temperature was 19 °C, more than 30% of people felt tired under the moderate and heavy labor intensity, more than 20% of people appeared nauseous, meanwhile chest tightness was obvious. When the average indoor temperature was 21 °C, fatigue was already present at low metabolic intensity. In the later period, the degree of fatigue increased, there would be dizziness and headache, accompanied by varying degrees of physical discomfort. The extra weight of MDPC accelerated the blood circulation of human body, thereby increasing the heart load. With the increase of indoor temperature and labor intensity, the phenomenon of chest distress was the most obvious and accompanied the whole process.

### 3.5. The acceptable regions inside MDPC

According to the experiment data inside MDPC, combined with the subjective feelings obtained by the questionnaire, the division of acceptable regions inside MDPC was shown in Fig. 16 according to the enthalpy-humidity chart. They were clearly acceptable area, just acceptable area, just unacceptable area, clearly unacceptable area, each region was approximate parallelogram. Due to individual differences, some regions will cross. However, in general, as the parallelogram moved up right, the degree of human sensory acceptability became worse. High or low temperatures will affect the thermal comfort of human body. It was clearly acceptable for the area where the temperature was 27–28 °C and humidity was 35–40%.

The acceptable regions inside MDPC here were differed from the conventional thermal comfort area. Outside the comfort area was
the discomfort area, which was that although people felt uncomfortable, they could continue to endure and would not have much impact. The Acceptable regions had an application background, people felt not comfortable with MDPC, it just different from the degree of acceptance. Besides, if the clearly unacceptable region were reached, staff efficiency could be severely reduced and could even lead to staff shock, indicating that it is necessary to change shifts or change MDPC. So we divided it into four different acceptable areas, which was of great significance for monitoring the physical and mental health of medical staff. The grey area in Fig. 16 was the conventional thermal comfort area inside clothing on the enthalpy-humidity chart. It can be seen that the MDPC acceptable area (including clearly acceptable area and just acceptable area) compared to the conventional thermal comfort area inside clothing overall was offset to the low temperature direction of about 16%, humidity range inside clothing expanded by 10% towards low humidity. Due to the high tightness of MDPC, and the sweat caused by the movement cannot be discharged, the high humidity inside MDPC increases the temperature that people feel, resulting in a decrease in the actual temperature of the acceptable area of the human body, and it is easier to accept the low temperature and humidity clothing microenvironment.

4. Conclusions

By human experiment with different indoor temperatures and labor intensity, meanwhile comprehensive human physiological parameters and subjective thermal reactions, the thermal comfort inside MDPC were studied, and recommendations were made for improvement. The conclusions of the study showed that:

(1) The influence of different indoor temperatures on the temperature and humidity inside MDPC was about 1°C and 10%. It indicated that the environment inside MDPC could be improved by reducing indoor temperature. Accordingly, a cross intelligent adjustment mode was proposed, it is suggested that the hospital buildings should reduce the indoor temperature to 17°C in the place only used by medical staff with MDPC under the moderate and heavy labor intensity. In the presence of MDPC group and OC group simultaneously, take 18–20°C and 17°C cross-regulation.

(2) The labor intensity has little effect on the temperature inside MDPC, and it has a significant effect on the humidity under moderate and heavy labor intensity, and the humidity change was even more than 10% within 20 min, the subjective thermal comfort threshold of the subjects decreased by nearly 50%. It is suggested that the continuous working time of medical staff should be limited to less than two hours under only moderate and heavy labor intensity.

(3) In this experiment, the sensitivity of each part inside MDPC for temperature was: back > forehead > chest > upper arm > thigh. The degree of sensitivity of each part inside MDPC for humidity was: upper arm > back > chest > thigh > forehead. Therefore, the later improvement measures should concentrate on cooling the back, forehead, chest and upper arm, to obtain better benefits.

(4) The total theoretical models of working time, labor intensity, temperature and humidity inside MDPC were given in Eqs. (2) and (3), which were suitable for indoor temperatures of 17–21°C; theoretical models in different body parts were also given in Eqs. (4)–(7), which were suitable for indoor temperatures of 19°C and 21°C.

(5) The acceptable regions inside MDPC with approximate parallelogram were divided on the enthalpy-humidity diagram, which can be used to guide the development and design of MDPC.

This paper has the following limitation due to experimental conditions and the impact of the epidemic: the samples selected for this study included only young participants, and the unbalanced gender may lead to errors in the experimental results, which means the coefficient of equations needs to be corrected. If conditions permit later, samples should be added reasonably or simulated to continue to improve the research conclusions.
Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Thermal comfort test questionnaire

See Tables A1 and A2.

Table A1
Thermal comfort questionnaire (OC group).

| Date: | Code | Gender | Age |
|-------|------|--------|-----|
|       |      |        |     |

**Time of filling:**

1. Your current thermal sensation.
   - 1 cold
   - 2 cool
   - 3 slightly cool
   - 0 neutral
   - 1 slightly warm
   - 2 warm
   - 3 hot

2. Your current humidity sensation.
   - 1 very dry
   - 2 dry
   - 3 slightly dry
   - 0 neutral
   - 1 slightly humid
   - 2 humid
   - 3 very humid

3. Your current sweating sensation.
   - 0 none
   - 1 slightly sweating
   - 2 sweating
   - 3 sweating a lot

4. Your current thermal comfort.
   - 0 comfortable
   - 1 slightly uncomfortable
   - 2 uncomfortable
   - 3 very uncomfortable
   - 4 beyond sufferance

5. Your current degree of acceptability.
   - 2 clearly unacceptable
   - 1 just unacceptable
   - 1 just acceptable
   - 2 clearly acceptable

6. Your current body condition. Fatigue:
   - 0 not tired
   - 1 slightly tired
   - 2 very tired

   Nausea:
   - 0 not nausea
   - 1 slightly nausea
   - 2 very nausea

   Dizziness and headache:
   - 0 not dizziness and headache
   - 1 slightly dizziness and headache
   - 2 very dizziness and headache

   Chest distress:
   - 0 not chest distress
   - 1 slightly chest distress
   - 2 very chest distress

   Dry eyes:
   - 0 not dry
   - 1 slightly dry
   - 2 very dry

7. The most desired body parts to improvement at this time.
   - forehead
   - chest
   - back
   - upper arm
   - thigh
   - shank
   - instep
   - others

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Table A2
Thermal comfort questionnaire (MDPC group).

| Date: | Code | Gender | Age |
|-------|------|--------|-----|
|       |      |        |     |

**Time of filling:**

1. Your current thermal sensation.
   - 1 cold
   - 2 cool
   - 3 slightly cool
   - 0 neutral
   - 1 slightly warm
   - 2 warm
   - 3 hot
   - 4 very hot

2. Your current humidity sensation.
   - 0 Neutral
   - 1 Slightly humid, the skin feels a little damp.
   - 2 Humid, the skin feels damp.
   - 3 Very humid, the skin feels very damp.

3. Your current sweating sensation.
   - 0 none
   - 1 slightly sweating
   - 2 sweating
   - 3 sweating a lot

4. Your current thermal comfort.
   - 0 comfortable
   - 1 slightly uncomfortable
   - 2 uncomfortable
   - 3 very uncomfortable
   - 4 beyond sufferance

5. Your current degree of acceptability.
   - 2 clearly unacceptable
   - 1 just unacceptable
   - 1 just acceptable
   - 2 clearly acceptable

6. Your current body condition.
   - Fatigue:
     - 0 not tired
     - 1 slightly tired
     - 2 very tired

   Nausea:
     - 0 not nausea
     - 1 slightly nausea
     - 2 very nausea

   Dizziness and headache:
     - 0 not dizziness and headache
     - 1 slightly dizziness and headache
     - 2 very dizziness and headache

   Chest distress:
     - 0 not chest distress
     - 1 slightly chest distress
     - 2 very chest distress

   Dry eyes:
     - 0 not dry
     - 1 slightly dry
     - 2 very dry

7. The most desired body parts to improvement at this time.
   - forehead
   - chest
   - back
   - upper arm
   - thigh
   - shank
   - instep
   - others
