Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Development of a negative pressure hood for isolation and transportation of individual patient with respiratory infectious disease

Limei Hao, Jinhui Wu, Jinming Zhang, Zhangyi Liu, Ying Yi, Zongxing Zhang, Enlei Zhang, Jiancheng Qi

Abstract

The frequent and sudden occurrence of both known and unknown infectious diseases can cause global social panic. If the source of infection can be effectively controlled in the early stages of an outbreak, the spread of infectious diseases can be prevented. In view of this situation, this study developed for infectious or suspected infectious patients a negative pressure isolation hood which effectively achieves direct individual isolation during the early stages of disease outbreak, and facilitates long-distance transport. The hood body is made of flexible transparent polyvinyl chloride (PVC) material, and the combination of the hood material is airtight. The unique inflatable column support structure and the design of the inflatable neck sleeve effectively ensure both stiffness and air tightness of the hood body. The electrical exhaust system maintains a stable negative pressure environment inside the hood, and polluted air inside the hood can be purified by a high efficiency filter. Test results showed that the internal noise of the hood was 68 ± 1 dB (A), the air exhaust volume of the electric exhaust system was not <200 L/min, and the filtration efficiency of the filter to 0.3 μm particles was >99.99%, indicating that the hood achieved effective isolation protection for patients with respiratory infectious diseases.

1. Introduction

In recent years, the outbreaks of respiratory infectious diseases caused by influenza A virus, Ebola virus and MERS-CoV Virus have caused widespread concern in the international community. Those infected with respiratory infectious diseases carry a large number of highly pathogenic respiratory microorganisms, and are moving sources of infection. Generally, pathogenic microorganisms are transmitted to the environment or individuals by means of respiration, speech, and contact, which can easily lead to concentrated infection in large-scale populations. The physical isolation of those infected with respiratory infectious disease is a simple and effective measure to control the source of infection and cut off the route of transmission [1]. The technical form of isolation is negative pressure isolation. The basic principle is to isolate infectious patients from the outside world through specialized ventilation and isolation devices though an artificial pressure barrier between the internal and external environment. The air discharged from ventilation must be purified to ensure no environmental harm [2]. According to the characteristics of the isolation equipment, they can be divided into fixed negative pressure isolation treatments and mobile negative pressure isolation transport. The negative pressure isolation ward [3,4] can realize negative pressure isolation treatment of many respiratory infectious patients. The US Center for Disease Control and Prevention (CDC) published the Technical Manual for the Prevention and isolation of Infectious Diseases in General Hospitals that provides a blueprint for the design of a negative pressure isolation ward [5]. Negative pressure ambulances [6], and transfer cabins [7,8] are classified as mobile negative pressure isolation transfer equipment that can safely transfer infected individuals to a hospital center or city hospital. After the outbreak of SARS in China in 2003, negative pressure isolation chambers and negative pressure ambulances were used to isolate and transport those infected, which effectively reduced the spread of the virus during transportation [9]. In 2014, the United States, Spain and France used negative pressure isolation cabins when transporting individuals infected with Ebola virus [8]. Negative pressure isolation transfer technology and equipment has thus emerged as an important means to control epidemic respiratory infectious diseases globally.
The currently existing negative pressure isolation transfer cabin can carry one patient over a short distance using a stretcher and an associated vehicle, and is suitable for seriously infected patients who are unable to walk or sit. There are drawbacks to this type of isolation. Firstly, it is impossible to isolate patients for an extended time period and the psychophysiological burden and harm to a patient lying in the isolation transfer cabin can be serious. Secondly, for patients with mild symptoms who can walk freely, it is not necessary to maintain a consistent lying position. In addition, microorganisms are typically spread to the environment through respiration, coughing, speaking, and vomiting, which are concentrated above the chest. Whole body isolation provides increased safety, this significantly increases the burden of patients and causes difficulties during diagnosis and treatment.

In this study, we report the design of an isolation negative pressure hood that is suitable for sitting, standing and lying. Related biosafety indexes of the hood, including its ability to prevent the diffusion of biological aerosols formed by the user is filtered through the high efficiency particulate filter, clean air is discharged safely. The continuous air flow significantly reduces humidity and heat accumulation, improving the thermal comfort of the user, reducing their physiological burden.

The electrical exhaust system is composed of a shell, a control module, a lithium battery and a fan. The battery is connected to the power charging port, and the battery is connected to the fan through an adjustable voltage source circuit. The impeller is connected to the integrated circuit board through an extended air volume monitoring circuit (Figure 2). A rotating impeller is arranged at the air outlet of the fan, and the Hall sensor is installed on the impeller and connected to the integrated circuit board. The control panel provides a waterproof switch, a low power alarm and a low air volume buzzing alarm that is connected to the integrated circuit board. The designed air volume of the electrical exhaust system is $\geq 200$ L/min.

2. Materials and methods

2.1. Bacteria and materials

The *Serratia marcescens* (8039) strain was purchased from the China Center of Industrial Culture Collection (CIICC). Nutritious broth liquid medium and nutritious broth Agar medium were purchased from Beijing Oboxing Biology Co., Ltd.

The instruments included an TSI8386A/9565A air multi-parameter tester (American TSI) with range of 0 to 50 m/s, a MP100 pressure gauge (French KIMO) of precision class 1, an AWA5661–2 sound level meter (Hangzhou Aihua instrument Co., Ltd., China) with a measuring range of 30–140 dB and accuracy of grade 1, a portable positive and negative pressure protective equipment testing box (National Bio-Protection Engineering Center of China) used for high efficiency filter filtration efficiency testing.

2.2. Structural design

As shown in Figure 1, the transparent hood consisted of an intake valve, inflatable air column, half-body cover, exhaust pipe, high efficiency particulate air filter, electrical exhaust system and back negative system. The structure of the inflatable column was adopted to ensure that the hood body was maintained in an upright position when the interior of the hood was under negative pressure. The hood can be folded once the air column was deflated, which is convenient for storage and transportation. The inflatable structure at the neck was used to fix the hood at the head, allowing it to adapt to infected individual, so that their head forms a relatively closed space.

2.3. Design of the electrical exhaust system

In this design, the electrical exhaust system forms a stable negative pressure hood through the suction of the fan. Fresh air is inhaled into the hood through the intake valve, allowing the user to breathe. After the biological aerosol formed by the user is filtered through the high efficiency particulate air filter, clean air is discharged safely. The continuous air flow significantly reduces humidity and heat accumulation, improving the thermal comfort of the user, reducing their physiological burden.

The electrical exhaust system is composed of a shell, a control module, a lithium battery and a fan. The battery is connected to the power charging port, and the battery is connected to the fan through an adjustable voltage source circuit. The impeller is connected to the integrated circuit board through an extended air volume monitoring circuit (Figure 2). A rotating impeller is arranged at the air outlet of the fan, and the Hall sensor is installed on the impeller and connected to the integrated circuit board. The control panel provides a waterproof switch, a low power alarm and a low air volume buzzing alarm that is connected to the integrated circuit board. The designed air volume of the electrical exhaust system is $\geq 200$ L/min.
2.4. Performance tests of the high efficiency particulate air filter

Filtration efficiency and resistance tests of the high efficiency particulate air filter were performed according to GB regulations (30864–2014) [10]. As the air exhaust volume of the negative pressure isolation hood was designed to be 200 L/min, the test flow rate was selected as 250 L/min.

According to 0.3 μm aerosol particles upstream and downstream, the filtration efficiency of the air filter was calculated according to formula (1) [11].

$$E = \left(1 - \frac{A_2}{A_1}\right) \times 100\%$$  \hspace{1cm} (1)

In the formula, E is the filtration efficiency of the filters (%), A₁ is the upstream aerosol particle concentration (particle/m³), and A₂ is the downstream aerosol particle concentration (particle/m³).

2.5. Performance tests of the negative pressure isolation hood

2.5.1. Negative pressure in the hood

The negative pressure difference of the isolation hood can be divided into static (if not worn) and dynamic (if worn by the user) differences. When testing the static pressure difference, the isolation hood was placed on a simulated individual and the inflatable sealing ring at the neck was filled. A pressure measuring tube was then placed inside of the hood and the electrical exhaust system was initiated. Following stabilization, the static pressure differences in the hood were assessed [12]. The dynamic pressure difference was measured in simulated and actual individuals. The simulated respiration device was used to test the dynamic pressure differences with different tidal volumes and respiration times. In the real person model, six workers (3 males and 3 females) were randomly selected undertake static uniform respiration, deep respiration, walking uniform respiration and deep respiration when wearing the isolation hood. Variation curves of the pressure differences were drawn.

2.5.2. Noise from the isolation hood

The hood was worn on a simulated human and the sealing ring at the neck was filled with air. The noise meter was fixed next to the simulated human ear and the electrical exhaust system was initiated. The noise in the hood was assessed after stabilization [12].

2.5.3. Exhaust air volume and continuous working times of the hood

The exhaust air volume of the electrical exhaust system was tested according to the GB30864–2014 method [10]. The electrical exhaust system was charged to assess the exhaust volume when empty (the exhaust duct was not connected to the negative pressure hood) and in the loaded state (the exhaust duct was connected to the negative pressure hood) (Figure 3). The electric exhaust system was placed in a sealing box with an opening at one end, so that the exhaust duct could be connected to the negative pressure isolation hood and ensure the seal where the exhaust duct was connected to the box. This ensured that the seal and exhaust duct were connected to the box. A round mouth was opened at the other end of the box to allow the test tube (diameter: 50 mm) to be inserted. The connector was sealed and the wind speed was assessed at the opening of the test tube. Five points at the cross-sectional area were measured on each occasion. Since the electric exhaust system was electric, it was assayed every 20 min until it automatically shut down. The low power alarm at the upper limit of the continuous working time was recorded. Loading

| Particle size (μm) | Average upstream filter concentration (unit/L) | Average upstream filter concentration (unit/L) | Average filtration efficiency (%) |
|-------------------|-----------------------------------------------|-----------------------------------------------|----------------------------------|
| 0.3               | 99.99488                                      | 99.99035                                      | 99.9921                          |
| 0.5               | 100                                           | 100                                           | 100                              |
| 0.7               | 100                                           | 100                                           | 100                              |
| 1.0               | 100                                           | 100                                           | 100                              |
| 2.0               | 100                                           | 100                                           | 100                              |
| 5.0               | 100                                           | 100                                           | 100                              |

Figure 3. Schematic diagram of the exhaust air volume tests of the electrical exhaust system.

Figure 4. Front, side and rear images of a hood user.
and non-loading conditions were assessed. The respiration tube that was connected to the hood was removed, and the wind speed was measured at the mouth of the respiration tube. The air exhaust volume of the electrical exhaust system was calculated according to formulas (2) and (3).

The specific method was to use an air multi-parameter tester to measure the wind speed at five points of the cross-sectional area of the respiratory tube. The supply air volume was calculated according to the formula.

\[ v = \frac{v_1 + v_2 + v_3 + v_4 + v_5}{5} \]  
\[ Q = 3600 \times vS \]  

Note: \( v \) is the average wind speed (m/s), \( V_n \) is the wind speed at the measuring point (m/s), \( Q \) is the average air volume (m\(^3\)/h), \( S \) is the test tube.

3. Results

3.1. Negative pressure isolation hood

As shown in Figure 4, the overall structure of the hood is soft and part of the hood is completely transparent, which is convenient for medical observations. The design of the electrical exhaust system and air inlet allows fresh air to flow into the hood. The overall mass of the hood is 2.5 kg, and the backpack negative pressure exhaust system can be removed and placed onto other parts of the body in order to allow the user to sit or recline. The average noise inside the hood is 68 ± 1 dB (A), which provides a quiet wearing environment. The hood can run continuously for 4 h.

Figure 5. Variation of the air exhaust volume of electrical system during continuous use of the hood.

Figure 6. Changes in the internal pressure of the hood when worn by a simulated individual. (A-C) Curves of the changes in pressure. (D) Maximum and minimums of all working conditions. Note: (A)-(C) 1 to 20 refers to tidal volumes of 1 L and respiration times of 20 breaths/min. The resting rates are identical. (D) 0 = static state. 1 to 4: tidal volume of 1 L/min, a respiration time of 20 to 50; 5 to 8: tidal volume of 1.5 L/min, respiration time of 20 to 50; 9–10: tidal volume of 2 L/min, respiration rate of 20 to 30; 11–12: tidal volume of 2 L/min, and a respiration rate of 20–30.
3.2. Performance of the isolation hood

3.2.1. High efficiency particulate air filter

The performance of the high efficiency particulate air filter directly determines whether the air discharged into the atmosphere is clean. Assessment of the filtration efficiency for particles of different sizes are shown in Table 1. Ten high efficiency filters were tested, of which the filtration efficiency for 0.3 μm particles was ≥99.99%. For particles ≥0.3 μm, the filtration efficiency remained at ≥99.999% and the filter resistance was 180 Pa.

3.2.2. Air exhaust volume and continuous working times

The exhaust air volume of the electrical exhaust system under non-loading and loading states was assessed. The exhaust air volume was tested every 20 min and the low power alarm was initiated when the electric exhaust system ran for 250 min. The experiment lasted 260 min. The relationship between the running time of the hood and the air volume is shown in Figure 5. The exhaust air volume was 230 L/min at full power, when running continuously for 4 h. The supply air volume was maintained at ≥200 L/min, which reached the continuous working time designed in this paper.

3.2.3. Differences in dynamic pressure

Stable negative pressure is an effective means of preventing the spread of pathogenic microorganisms to the environment. The continuous and stable existence of pressure differences can form a stable air flow from the high pressure to the low pressure area, preventing the diffusion of harmful

Table 2

| Work condition | 1    | 2    | 3    | 4    | 5    | 6    |
|---------------|------|------|------|------|------|------|
| A Minimum     | -22.46 | -17.67 | -13.96 | -66.04 | -28.83 | -57.09 |
| Minimum       | -53.57 | -40.63 | -18.57 | -85.67 | -69.84 | -95.34 |
| Maximum       | -23.54 | -12.24 | -14.59 | -44.34 | -21.83 | -47.24 |
| Minimum       | -83.77 | -31.86 | -60.62 | -124.55 | -97.24 | -114.15 |
| Maximum       | -23.45 | -15.50 | -14.23 | -50.22 | -31.77 | -33.04 |
| Minimum       | -65.14 | -43.35 | -41.36 | -111.53 | -74.36 | -82.68 |
| Maximum       | -18.12 | -16.76 | -15.32 | -3.07 | -29.29 | -24.45 |
| Minimum       | -90.10 | -55.01 | -62.88 | -144.05 | -111.07 | -103.39 |

Note: (A) Uniform respiration whilst standing still; (B) Deep respiration whilst standing still; (C) Uniform respiration whilst walking; (D) Deep breaths whilst walking. 1–3 are 3 female staff, and 4–6 are 3 male staff.
substances. During respiration, as long as the negative pressure is maintained, effective isolation and protection persist.

In this study, a simulated respiration device was used to test the effects of different tidal volumes and respiratory frequencies on the internal pressure differences of the isolation hood. The fluctuation of pressure differences was assessed when the number of breaths per minute increased from 20 to 50 at a tidal volume of 1 and 1.5 L, and 2 and 2.5 L when the number of breaths increased from 20 to 30 (Figure 6 A-D). Measurements of the pressure differences were performed for 10 min under each working condition, and the maximum/minimum and average values were calculated. As shown in Figure 6, with increasing tidal volume, the fluctuation of pressure differences increased at the same number of breaths. When the tidal volume was lower than 2 L/min, the pressure inside the hood was negative. When the tidal volume exceeded 2 L/min, positive pressure was observed. When the tidal volume was constant, the fluctuation of pressure difference increased with accelerated respiratory frequency. We selected six workers to wear the headdress whilst completing four working conditions, including standing still and uniform respiration for 2 min, standing still and deep respiration for 2 min, walking and uniform respiration for 2 min, and walking and deep respiration for 2 min. As shown in Figure 7 and Table 2, the pressure differences in the male hood were significantly larger under uniform respiration, and the fluctuation of pressure was significantly greater under deep respiration. Negative pressure in the hood was maintained at tidal volumes ≤ 1.5 L. The tidal volume of normal adults is ~ 600–700 mL [13]. The hood therefore ensures the effective control of the outward diffusion of biological aerosols during use.

4. Discussion

Respiratory pathogens rely on air transmission, whilst non-respiratory infectious pathogens are transmitted through the air and through contact. Very few individual virions or cells of respiratory pathogens such as adenoviruses, tuberculosis, plague, and SARS virus are required to cause human infections. Approximately 1/10 tuberculosis pathogens cause infections and as little as 200 rhinovirus particles cause the common cold [14]. Coughing produces thousands of particles, sneezing produces hundreds of thousands of particles, and contagious colds produce 6200 active viral droplets per hour that can spread in the air for ≥ 10 min [15], explaining the rapid transmission of respiratory pathogens. During the latent period of infection, a large number of pathogenic microorganisms will spread to the outside environment, leading to the infection of surrounding individuals.

At present, the major mechanism to prevent pathogenic microorganisms spreading to the outside environment is physical isolation, including the wearing of masks, isolation clothes, the use of negative pressure isolation cabins, negative pressure ambulances, and negative pressure wards. The efficiency of individual masks is low, and provides limited protection. Negative pressure ambulances fail to overcome the issues of pathogenic microorganisms diffusion in the process of patients moving from family, epidemic focus and complex environment to ambulance. Negative pressure isolation transfer capsules are effective in preventing the spread of pathogenic microorganisms during transport processes. However, the patients must lie flat and require specialized personnel and manpower to carry the infected individual. In addition, the patients bear a greater physical and psychological burden, leading to difficulties during treatment. In patients who can walk independently, local negative pressure isolation not only prevents the spread of pathogenic microorganisms, but enables those infected with a greater freedom of movement, permitting rapid and flexible isolation transport. In this study, we designed a local negative pressure isolation hood for patients with respiratory infectious disease, which provided a respiratory and craniofacial locally isolation environment for patients with mild symptoms or suspected infections. The system ensured that the pathogenic microorganisms exhaled by personnel were effectively intercepted, protecting the safety of health care personnel. The hood did not affect the movement of the user who required no additional assistance, thus reducing manpower.

5. Conclusions

The negative pressure isolation hood developed in this study provides a useful supplement to negative pressure isolation transfer cabins. For mild or suspected patients, the isolation hood is an ideal choice. The hood not only achieves isolation and protection, but permits the mass transit of a large number of individuals, ensuring that during the beginning of an outbreak, greater isolation can be achieved during transport. The hood therefore permits the rapid and flexible transfer of infected individuals and could prevent public health emergencies and the spread of respiratory infectious disease.

Acknowledgements

Thanks for the funding projects of Ministry of Science and Technology of the People’s Republic of China: Major infectious diseases such as AIDS and viral hepatitis prevention and control of major projects of China (2017ZX10304403–004–001).

Conflict of interest statement

The authors declare that there are no conflicts of interest.

References

[1] N.J. Jiang, Design points of airborne infectious diseases negative pressure isolation ward, C&CA/C. 4 (2018) 49–50 (in Chinese). https://doi.org/10.3969/j.issn.1005-3296.2018.04.013.

[2] The Ministry of Health of the People’s Republic of China, Technical Specification for Hospital Isolation, 2009 (in Chinese).

[3] J.C. Qi, Z. Wang, X.X. Xu, M.X. Li, H.T. Wang, K. Yang, H. Han, Design, construction and management of negative pressure isolation ward for infectious diseases (II) - analysis of main technical indicators and human comfort indicators, Chin. Med. Equip. J. 25 (2004) 37–38 (in Chinese). https://doi.org/10.3969/j.issn.1003-8868.2004.02.019.

[4] S. Kang, J. Yoon, H. Jhun, B.W. Lim, S.M. Ko, E. Park, J.H. Hwang, S.Y. Lee, S.U. Lee, T.R. Cha, W.C. Shin, T.G. Sim, M.S. Jo, J. Joon, The utility of preliminary patient evaluation in a febrile respiratory infectious disease unit outside the emergency department, J. Korean Med. Sci. 4 (suppl. 1) (2017) S187–S188. https://doi.org/10.1093/ofid/ofx163.349.

[5] L. Sehulster, R.Y.W. Chinn. Guidelines for Environmental Infection Control in Healthcare Facilities. The US Center for Disease Control and Prevention (CDC) and the Healthcare Infection Control Practices Advisory Committee (HICPAC).

[6] Y. Yi, M. Zhao, Y.J. Li, Z.X. Zhang, J.C. Qi, Development and application of negative pressure ambulance exhaust filtration equipment, Chin. J. Public Health Eng. 11 (2012) 89–96. doi: CNKI:EN-US-2012-02-002.

[7] J.C. Qi, Z. Wang, X.X. Xu, Q.S. Li, H.T. Wang, H. Han, Design, construction and management of negative pressure isolation wards for infectious diseases (I), Special Requirements for Structural Layout, Internal Facilities and Design and Construction, Chin. Med. Health Equip. 1 (2004) 46–48 (in Chinese), doi:CNKI:EN-US-2004-01-025.

[8] M.X. Hu, New Progress in Research on Negative Pressure Isolation Equipment for Transporting Ebolea Patients at Home and Abroad, Chin. Med. Health Equip. (2004) 150 (in Chinese).

[9] J.N. Li, D. Song, Application of Negative Pressure Isolation Chamber in SARS Transportment. Paper Presented at the 2003 National Symposium on SARS Prevention and Control, 2003 (in Chinese).

[10] General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China, Zhong, GB 30864-2014 Respiratory Protection Power Supply Air Filter Respiratory in China Standard Publishing House, 2014 (in Chinese).

[11] Y.Z. Zhang, Efficiency and Resistance of Performance Test Method for High Performance Air Filters, China Standards Press, 2009 (in Chinese).

[12] E.C. f Standardization, EN 943-1:2015 protective clothing against dangerous solid, liquid and gaseous chemicals, Including Liquid and Solid aerosols, Part1: Performance Requirements for Type1 (Gas-Tight) Chemical Protective Suit[S], 2009.

[13] M.M. Wang, M. Ge, W.Q. Yin. (2009) The relationship between normal reference value of tidal volume and geographical factors for Chinese adults, Journal of Xian Academy of Arts and Sciences (Natural Science Edition). 12, 5–9. (in Chinese). doi:CNKI:SUN:ZGWX.0.2012-02-002.

[14] A. Hyvärinen, M.K.O. Rourke, J. Meldrum, L. Stetzenbach, H. Reid, Influence of cooling type on airborne viable fungi, J. Aerosol Sci. 26 (1995) S887–S888. https://doi.org/10.1016/0021-8502(95)97351-E.

[15] Y.Z. Ji, Numerical Study on Air Organization and Negative Pressure Control in Infectious Isolation Ward, Dissertation Tianjin University, 2005 (in Chinese).