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Research on Reliability Evaluation of Plateau Emergency Rescue Ventilator based on Four Comprehensive

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Abstract

The harsh natural environment of high-altitude regions leads to frequent emergencies. As a critical piece of equipment in emergency rescue, the reliability of ventilators directly impacts treatment efficiency and patient safety. This study aims to evaluate the ventilator's start-up capability, operational stability, and performance maintenance under typical high-altitude transportation conditions. Using the Chengdu-Lhasa high-altitude transportation route as the research background, a specific model of ventilator was selected as the research object. A comprehensive environmental testing platform was used to simulate the combined effects of four environmental stresses: temperature, humidity, vibration, and low air pressure. A full-process test operation covering pretreatment, initial testing, operational loading, performance monitoring, and recovery was conducted on the ventilator. The study found that the ventilator faces a risk of start-up failure under the coupled conditions of low air pressure and low temperature. However, during operation, its performance indicators (such as control accuracy) still meet requirements under vibration and low-pressure interference. It is recommended to optimize the ventilator's structural design and high-altitude environmental adaptability testing procedures to provide a basis for the selection, deployment, and standardization of high-altitude emergency medical equipment.

Keywords

Plateau Area; Four Comprehensive Environmental Tests; Ventilator; Environmental Adaptability.

1. Introduction

The high altitude, low air pressure, and cold and complex climate of Lhasa and other plateau regions in Tibet make them typical areas in my country with frequent natural disasters and inconvenient transportation[1]. In the event of an emergency, whether emergency rescue equipment can be quickly deployed and operate stably is a key factor in the success of the rescue[2]. As the core equipment of the modern emergency medical system, the ventilator plays an irreplaceable role in supporting respiratory function and prolonging rescue time[3]. However, the external stresses such as low air pressure, large temperature difference, and strong vibration in the plateau environment pose a significant threat to the start-up performance and stable operation of the ventilator[4, 5]. Although there has been some progress in the environmental adaptability research of medical equipment at home and abroad in recent years, there is still a lack of systematic verification research specifically for plateau emergency transportation scenarios, especially integrating multiple stress conditions such as temperature, humidity, low air pressure and vibration. This paper takes a certain model of ventilator as the test prototype, combines the actual environmental conditions of the typical transportation route from Chengdu to Lhasa, and uses a four-integrated environmental test platform to conduct a systematic reliability assessment of it, focusing on analyzing its start-up success rate, the changing trend of key performance parameters and its operational stability under different typical working conditions.

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2. Test Basis and Referenced Documents

GB/T 14710-2009 "Environmental Requirements and Test Methods for Medical Electrical Appliances"; GJB150.24A-2009 "Laboratory Environmental Test Methods for Military Equipment Part 24 Temperature-Humidity-Vibration-Altitude Test"; Based on the standards, this study tailored the temperature change rate and vibration spectrum according to actual transportation data at high altitudes to ensure that the test stress was "both standard and suitable for high altitudes".

3. Test Prototype and Installation

The test prototype was a portable ventilator, consisting of a main unit, turbine module, proportional valve, oxygen sensor, and a 7.4V/6.8Ah lithium battery [6]. The fixture was made of 6082-T6 aluminum alloy and milled as a whole to ensure that the first-order natural frequency was >2000Hz, avoiding coupling resonance with the vibration table [7, 8]. The system recorded the internal turbine speed, proportional valve opening, and original ADC value of the sensor in real time via RS-485, providing data for subsequent failure tracing.

4. Test Conditions

4.1. Transportation-Use Link

The environmental simulation test selected Lhasa, Tibet as a typical high-altitude emergency rescue destination, simulating the winter season in the Lhasa region to fully reflect the extreme natural environmental characteristics such as low temperature, low air pressure, and dryness. The transportation route was set according to the actual emergency rescue material allocation process, starting from Chengdu, transported by air to Lhasa Gonggar Airport, and after experiencing conditions such as high-altitude low air pressure, temperature and humidity changes, and flight vibrations, transferred to road transport to the final emergency rescue site, traversing multiple complex road sections with high altitudes and harsh climates. This route has typical characteristics such as strong representativeness, diverse stresses, and sudden environmental changes, providing a scientific and rigorous test scenario basis for the environmental adaptability assessment of emergency equipment such as ventilators.

4.2. Test Stress Parameters and Test Sequence

Table 1. Test stress parameters and time series

Time (h)	Temperature(℃)	Relative humidity(%RH)	High (km)	Work status	Vibration
0	-5	60	0.5(95.2kPa)	Power off	Air transport 3 hours
0.5	20	25	4.57(49.3kPa)		
3	20	25			
3.5	-21	≤30	3.65(59.4kPa)		45 minutes by road
24	-21	≤30		Power on	No vibration

Based on the environmental characteristics of the actual transportation route from Chengdu to Lhasa, Tibet, the typical natural stresses experienced during the journey were comprehensively analyzed, including high-altitude low air pressure, drastic diurnal temperature differences, air humidity fluctuations, and multi-source mechanical vibrations. This paper relies on a comprehensive environmental test platform to conduct environmental adaptability verification close to actual combat conditions. The experiment accurately reproduced the representative stress curve of Lhasa region in winter by simulating the entire process of air and road

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transportation. An experimental profile was designed incorporating four coupled stresses: temperature, humidity, air pressure, and vibration. Scientifically sound stress parameters and loading sequence arrangements were established to ensure the representativeness, repeatability, and engineering guidance significance of the experiment. Specific stress parameters and timing arrangements are detailed in Table 1.

4.3. Test Stress Profile

In order to realistically reproduce the typical environmental conditions faced by emergency medical equipment during the transportation from Chengdu to Lhasa, this paper constructs a comprehensive test profile covering three stresses: temperature, humidity and low air pressure [9], and simulates the variation law of actual environmental factors such as different altitudes, diurnal temperature differences and dry climates in the transportation route. In the test profile, the temperature range is set from 20℃ to -21℃, the humidity drops from 60%RH to ≤30%RH, and the air pressure corresponds to an altitude that gradually changes from 0.5km to 4.57km, fully reflecting the extreme environmental characteristics of the plateau transportation stage. The parameter variation curve is shown in Figure 1. At the same time, in order to accurately simulate the dynamic mechanical stress borne by the equipment during transportation, this paper refers to the typical working conditions of road truck transportation (vertical, lateral and longitudinal) and jet aircraft cargo hold transportation, collects and loads the acceleration power spectral density curves in the corresponding directions [10]. The detailed spectral density data are shown in Figures 2 to 5, which provide a basis for the load input of the vibration test.

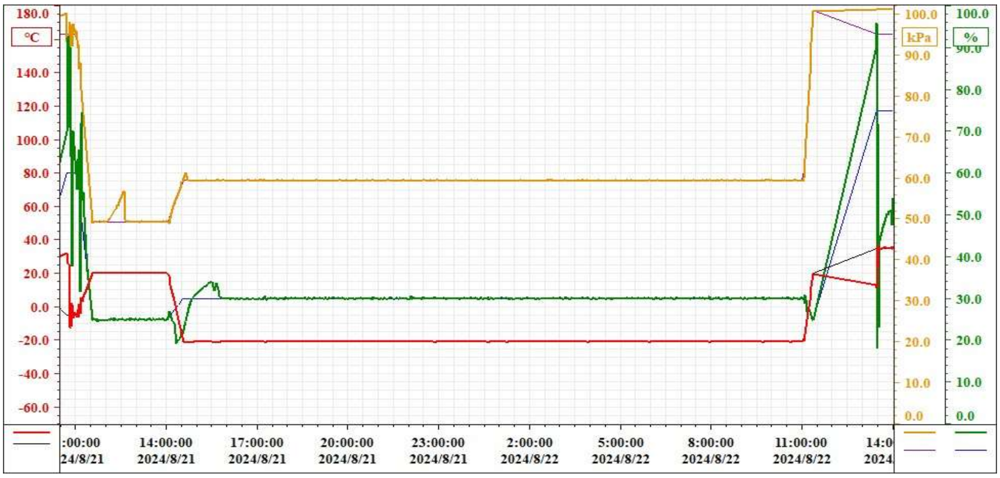

Figure 1. Stress profile of temperature-humidity-low pressure simulation test

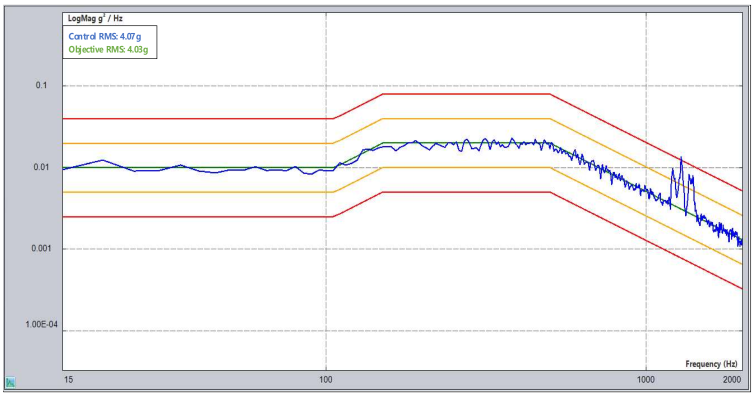

Figure 2. Power spectrum density diagram of the simulated Lhasa airborne transport test

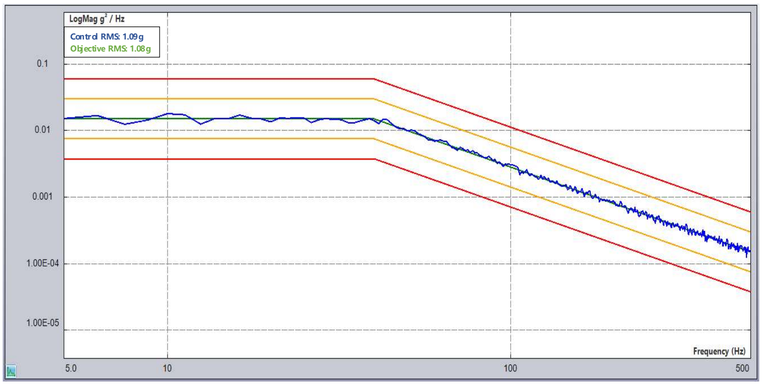

Figure 3. Power spectrum density diagram of the simulated vertical transport test on the Lhasa highway

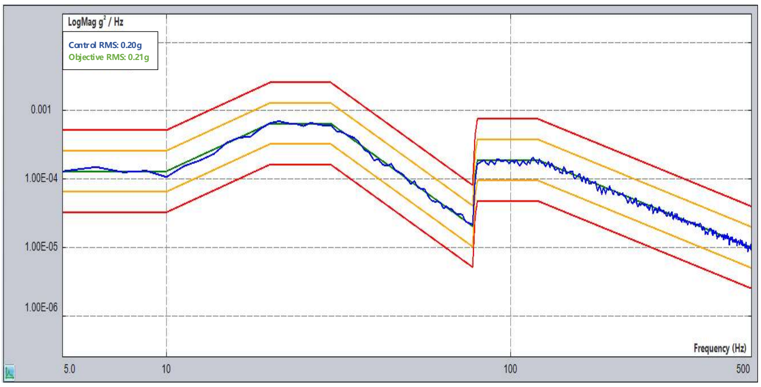

Figure 4. Power spectrum density diagram of the simulated Lhasa highway lateral transport test

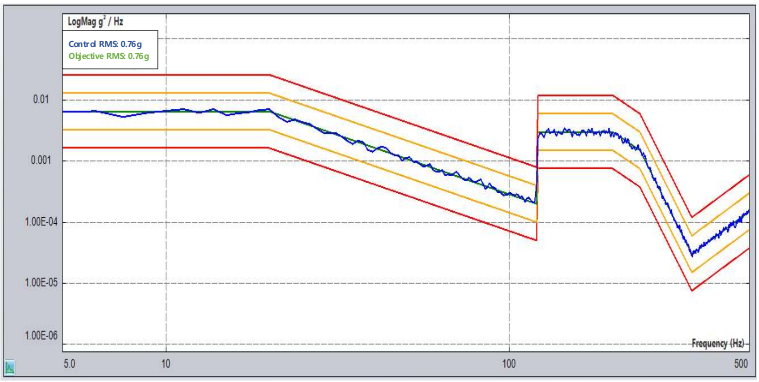

Figure 5. Power spectrum density diagram of the simulated Lhasa highway lateral transport test

4.4. Test Procedure

To ensure the test prototype reaches thermal equilibrium under standard environmental conditions, it is first placed under normal (or reference) environmental conditions until the temperature stabilizes. Subsequently, initial performance tests are performed on the test sample under standard atmospheric conditions, and relevant data are recorded in detail. The performance of the test sample must be measured and recorded during each test cycle. Performance testing should be conducted under representative environmental conditions within the experimental profile, specifically at 3.5 hours and 24 hours.

According to the established test method, the test prototype is placed in the four-dimensional integrated test chamber and fixed to the vibration table surface using appropriate fixtures to

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ensure its stability. Before the test begins, a pre-inspection is performed on the test prototype to confirm that its power-on/off functions and performance indicators are normal. Subsequently, the test chamber is operated according to the test stresses shown in Figures 1 to 5, and test data are recorded in detail. After the test, subsequent tests are performed on the test prototype, and test data is recorded to complete the entire test procedure.

The temperature of the test chamber should be restored to standard atmospheric conditions at a rate not exceeding 1℃/min, while the rate of change of relative humidity should be controlled to not exceed 10%RH/min, and the rate of change of altitude (air pressure) should not exceed 10m/s, until the test sample has completely reached a stable temperature and humidity state.

5. Key Performance Indicators

5.1. Tidal Volume

Tidal volume, infants: 20ml~100ml (BTPS); children: 20ml~300ml (BTPS); adults: 100ml~4000ml (BTPS); control accuracy: ±(10ml+10% of the set value)[11].

5.2. Output Oxygen Concentration

Adjustable range of output oxygen concentration: 21%~100%, control accuracy: ±(3vol.%+1% of the set value)[12].

5.3. Peak Airway Pressure

Peak airway pressure setting range: 1~60cmH2O; control accuracy: ±(2cmH2O+5% of the set value)[13]. Note: The pressure setting range is the value after the pressure control level is superimposed with PEEP.

5.4. IPR Ratio

IPR ratio, 2:1~1:4: ±10% of the set value; other ranges: ±15% of the set value[14]. 4.5 Positive End-Expiratory Pressure Positive end-expiratory pressure, 0cmH2O~2cmH2O: The positive end-expiratory pressure is set to 0cmH2O, with an error not exceeding 2cmH2O); 2cmH2O~50cmH2O (excluding 2cmH2O): ± setting value (2cmH2O + 5% of the setting value) [15].

6. Conclusion

Simulation results showed that the initial startup failure rate of the ventilator was 33.3% under simulated altitude conditions of 4.57 km, air pressure of approximately 49.3 kPa, and a temperature of -21°C. However, when the air pressure recovered to 59.4 kPa while the temperature remained at -21°C, the startup success rate returned to 100%. This indicates that low air pressure is the dominant factor affecting the ventilator startup success rate. The deviations of key parameters such as tidal volume, oxygen concentration, and airway pressure were all controlled within the standard range at each operating condition stage. However, parameter fluctuations were slightly enhanced during vibration loading, and momentary alarms occurred at certain times, but these did not lead to equipment shutdown.

This study systematically evaluated the environmental adaptability of a certain type of ventilator along a typical transportation route from Chengdu to Lhasa using a four-dimensional comprehensive environmental testing platform. The test results show that this model of ventilator possesses strong operational stability and control precision, but there is a risk associated with startup under extremely low air pressure conditions. It is recommended that environmental adaptability screening tests be conducted in advance when deploying such emergency medical equipment in high-altitude areas in the future; that air pressure compensation mechanisms or power preheating modules be introduced into the equipment structural design to improve the success rate of the first start-up in high-altitude areas; and that the research results be transformed into factory verification specifications for high-altitude transport medical equipment to improve the level of medical emergency response to sudden events in high-altitude areas.

Acknowledgments

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