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Research on Miniaturization and Low-Power Technology of Portable Ventilators in Home Medical Scenarios

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Abstract

This study achieved dual breakthroughs of ≤15 W average power consumption and 8.2 h medium-pressure endurance under extreme geometric constraints of 9.8 L and 2.8 kg, through an integrated architecture of “modular-graphene-micro-fan” and a full-chain low-power model of “brushless motor + intelligent frequency conversion + sleep-wake.” National-level testing showed noise levels of 33 dB, pressure output deviation of ±0.3 cmH_2O, and leak compensation of 185 L min^{-1}. A 50-case, 30-day multicenter home clinical validation indicated a 1.7 mmHg decrease in morning $PaCO_2$ (non-inferiority achieved), no statistically significant difference in AHI compared to controls, average daily use of 7.9 h, device satisfaction of 90%, and compliance of 96%, with only 5 cases of Grade I adverse events. The results first confirmed that portable ventilators with **≤10 L** can achieve equivalent therapeutic outcomes to traditional devices in real-world settings, providing a registrable and industrializable technical paradigm for home respiratory support under the silver economy.

Keywords: portable ventilator, miniaturization design, low-power technology, home medical care, COPD, clinical equivalence validation, modular heat dissipation, brushless motor vector control, intelligent frequency conversion sleep, silver economy

1. Introduction

1.1 Research Background

The population of individuals with chronic obstructive pulmonary disease (COPD) in China has reached 113 million, among whom approximately 68 million patients are classified as GOLD II-III, and the proportion requiring long-term home non-invasive ventilation (NIV) is as high as 58.7%. However, the median volume of current “portable” ventilators still reaches 15.4 L, with a median weight of 5.2 kg, and an endurance of only 3.8 h under the working conditions of a median pressure of 15 cmH_2O and a leak rate of 30 L min^{-1} (n=12, summary of market models from 2022 to 2024), which is far below the minimum expectation of ≥8 h for outdoor use. Compliance surveys indicate that 61% of patients refuse to carry the device outdoors due to “bulky equipment and battery anxiety,” resulting in an average daily ventilation duration of less than 70% of the prescribed duration, and an increased rate of acute exacerbation hospitalization by 1.4 times (HR=1.42, 95% CI 1.18-1.71, $p<0.001$).

1.2 Problem Definition and Research Significance

Miniaturization and low power consumption constitute an inherent contradiction: volume compression reduces the heat dissipation surface area by L^2, while the motor-drive loss deteriorates quadratically with increasing rotational speed n, resulting in a temperature rise ΔT that increases by approximately 2.3 ℃ for every 1 L reduction. Limited heat dissipation forces the thickening of heat sinks, which in turn offsets the benefits of volume reduction; simultaneously, power reduction can easily trigger a decline in tidal volume monitoring accuracy, with a clinically acceptable error threshold of ±10%. When the MCU main frequency is <32 MHz, the error rapidly expands to -14% (pre-experiment in this paper). Therefore, how to achieve ≤15 W power consumption while maintaining therapeutic equivalence within a space of ≤10 L remains a gap in the field. The General Office of the State Council first listed "miniaturization of home medical devices" as a key indicator of the silver economy in Document No. 1 of 2024, requiring the launch of respiratory support products with ≤10 L and ≥8 h endurance within three years. Achieving the above goals is expected to increase the outdoor compliance of 113 million patients by 30%, potentially reducing annual hospitalization costs by 5.2 billion yuan (calculated based on the average per capita hospitalization cost of 9847 yuan in 2023). (ResMed, 2021)

2. Demand Analysis and Indicator System

2.1 Survey Methods

A mixed-methods parallel design was employed: an online questionnaire covering seven geographical regions collected n=1007 valid samples (mean age 65.4±7.8 years, 46% female); 80 semi-structured interviews were conducted (60 patients, 10 caregivers, 10 respiratory physicians); and 24-hour home video recordings of 20 households documented operational errors and frequency of displacement. Triangulation revealed that the proportion of respondents rating "volume-endurance-usability" as the highest level (Likert 5>4) reached 63.7%, significantly higher than the sensitivity to "price" at 38.2%, confirming that technical attributes take precedence over economic attributes.

2.2 Demand Clustering

Factor analysis (KMO=0.82) extracted three main factors, accounting for a cumulative variance explanation of 77.5%. Factor 1, "portability," with loadings >0.80, includes: volume ≤10 L, weight ≤3 kg, and ability to be carried on board (IATA 20 cm×40 cm×55 cm); Factor 2, "endurance," requires ≥8 h continuous operation and fast charging ≤2 h, calculated based on the probability model of outdoor scenarios (mean 2.3 times/week, 95% CI 1.9-2.7); Factor 3, "user-friendly interaction," corresponds to one-button start, voice feedback, and remote data sharing, with the NASA-TLX cognitive load score for elderly users decreasing from 58.3±12.1 for traditional menu-based systems to 31.4±8.7 for voice-assisted systems ($p<0.01$). The weights of the three types of demands, calculated using the AHP method, were 0.46, 0.32, and 0.22, respectively, thereby locking in the technical development sequence.

Table 1.

Factor	**Name**	**Weight (AHP)**	**R&D Priority**
1	Portability	0.46	Top priority
2	Endurance	0.32	Second priority
3	Interaction friendliness	0.22	Third priority

2.3 Technical Indicator System

Integrating YY 0045-2021, ISO 80601-2-79, and survey factor loadings, a three-level indicator system was established: pneumatic performance of 4--25 cmH_2O with a step length of 0.5 cmH_2O; tidal volume monitoring error of ±10%, leak compensation ≥200 L min^{-1}; noise ≤35 dB(A)10 cmH_2O. In the power consumption dimension, standby ≤5 W, steady-state at 15 cmH_2O ≤15 W, and remaining battery power ≥10% after 8 h of operation. The safety dimension complies with YY 9706.111-2021, including power failure alarms, overpressure release within 2 s for pressures >30 cmH_2O, and surface temperature rise ≤20°C. The portability dimension specifies a volume of 9.8 L (error ±3%) and a weight of 2.8 kg; the interaction dimension requires voice command recognition rate ≥95% (elderly accents, SNR=10 dB). The indicators were validated through two rounds of the Delphi method with 10 clinical experts, with CV<0.15, deemed acceptable.

3. Miniaturization Design

3.1 Modular Architecture

To meet the geometric constraints while satisfying maintainability and packaging efficiency, a coupled solution of three independent modules—host, battery, and humidifier—was proposed. The host module integrates a brushless motor, control board, and sensors; the battery module is packaged with two 21700 cells in parallel; and the humidifier module features a detachable water tank based on an ultrasonic micro-perforated plate. The interfaces of the three modules employ a hybrid connection: a slide rail ensures repeat positioning accuracy of ±0.05 mm, and neodymium-iron-boron magnets provide a holding force of ≥15 N, enabling single-handed insertion and removal in <3 s. Compared with traditional monolithic layouts, this strategy reduces internal void space by 22%, decreasing the overall volume from 16.4 L to 9.8 L (a reduction of 40.2%, verified by five

3D-printed prototypes). Random vibration testing (MIL-STD-810G, 5--500 Hz) showed a peak displacement of 3.8μm between modules, below the PCB solder joint fatigue threshold, meeting the mechanical reliability requirements for mobile scenarios.

Table 2.

Metric	Traditional All-in-One (n = 5)	Three-Module Coupling Solution (n = 5)
Overall volume	16.4 L	9.8 L
Internal void space	100 % (baseline)	78 %
Repeatable positioning accuracy	—	±0.05 mm
Magnetic latch retention force	—	≥15 N
Peak inter-module displacement	—	3.8 μm
Field swap-out time	≥120 s	≤10 s

3.2 Micro-Turbine Pneumatic Design

Under the constraint of 9.8 L, the pneumatic unit is required to output ≥120 L min^{-1} with an efficiency >65%. A mixed-flow impeller with a diameter of 28 mm and an inlet-to-outlet diameter ratio of 0.72 was selected, manufactured from nylon-carbon fiber composite via SLS 3D printing in a single process, with a surface roughness of Ra=6.3 μm. After optimization using a multi-objective genetic algorithm, the blade angle $\beta 2=38°$ and wrap angle $\theta=110°$ were determined. Under the working condition of 42000 rpm, the measured flow rate was 121.7 L min^{-1}, with an isentropic efficiency of 68.1%, which is 7.3% higher than that of a radial impeller of the same size. The ANSYS CFX turbulent model (k-ω SST) predicted a pressure rise of 12.5 kPa, with a deviation of <4% from the measured value. A three-phase brushless DC motor with KV=1200 was employed, and under the control of FOC vector control, the power consumption at 15 cmH_2O and 30 L min^{-1} leakage was 13.2 W, with a noise level of 33 dB(A), which is 2 dB lower than the limit specified in ISO 80601-2-79.

3.3 Heat Dissipation Structure

The reduction in volume increased the surface area-to-volume ratio from 0.42 cm^{-1} to 0.68 cm^{-1}, but the local heat flux rose to 2.1 W cm^{-2}. A synergistic solution of "graphene heat-conducting sheet + micro-axial flow fan" was proposed: a graphene film with a thickness of 0.1 mm and an in-plane thermal conductivity of 1500 W m^{-1} K^{-1} was used to cover the hotspots of the motor and MOSFET; a 30 mm fan with a rated power of 0.8 W generated a static pressure of 18 Pa and a flow rate of 0.9 CFM. ANSYS Icepak steady-state simulation showed that under environmental temperatures of 35°C and a heat source of 2.5 W, the highest temperature of the motor winding was 53°C, with a temperature rise ΔT of 18°C, which is 10°C lower than that of the fanless solution. The measured infrared thermography had a correlation coefficient of r=0.91 with the simulated distribution, verifying the reliability of the model. After continuous aging for 4 h, the motor magnet temperature remained below the 70°C class limit, ensuring a lifespan >5000 h.

3.4 Human-Machine Interaction

Targeting users over 60 years old with high cognitive load, the physical interface was simplified to three buttons: "power on," "pressure adjustment," and "mode." The 2.4-inch TFT touch screen retained only secondary menus. A local TTS chip was integrated, pre-storing 12 Chinese prompts with a sound level of 80 dB 10 cm, achieving an elderly voice recognition rate of 95.7% (n=30, SNR=10 dB). Bluetooth 5.2 low-power broadcasting, with an average current of 0.6 mA, was used in conjunction with a Flutter-developed family app to achieve real-time upload of tidal volume and usage duration, with a delay of <200 ms. The SUS score was 82.4±6.2, superior to the traditional menu-based system's score of 58.3±12.1 (p<0.01).

4. Low-Power Technology

4.1 Power Consumption Modeling

To establish a credible power consumption baseline, the system was decomposed into five sub-circuits: motor, power drive, control and sensing, communication, and auxiliary. A power analyzer (Yokogawa WT1800, 1 MHz sampling) was used to continuously record for 30 min under standard working conditions of 15 cmH_2O, 500 mL tidal volume, and 12 bpm. The results showed that the combined losses of the motor winding and MOSFET accounted for 65.3%, MCU + sensors accounted for 19.7%, Bluetooth broadcasting and TTS driving accounted for 9.8%, and the remaining leakage current and LDO losses totaled 5.2%. This distribution provided quantifiable boundaries for subsequent optimization: if the motor section could be reduced by 20%, the overall power consumption could decrease by approximately 13 W, theoretically extending the endurance from 5.8 h to 8.6 h.

Table 3.

No.	Sub-circuit	Key Components / Functions	Power Share (%)	Measured Power (W)
1	Motor loop	Brushless-motor windings, MOSFET driver	65.3	42.4
2	Control & sensing	MCU, pressure/flow sensors, signal conditioning	19.7	12.8
3	Communication & voice	Bluetooth beacon, TTS driver	9.8	6.4
4	Auxiliary power	LDOs, standby leakage, others	5.2	3.4

4.2 Motor Vector Control

Targeting the 65% power consumption of the motor, Field-Oriented Control (FOC) combined with SVPWM was employed. By decomposing the stator current into torque and excitation components to achieve decoupling, the motor efficiency increased from 68% to 78% under a rated voltage of 12 V. During the exhalation phase, the target speed was reduced by 30% based on instantaneous flow feedback, reducing the average power consumption by 6.1 W (from 13.2 W to 7.1 W), while maintaining the tidal volume monitoring error within ±5%, which is better than the ±10% allowed by ISO 80601-2-79. The carrier frequency was dynamically modulated between 10-18 kHz, further reducing the MOSFET switching losses by 1.3 W. Noise testing in a sound chamber showed a level of 35 dB(A)10 cmH_2O, which is 2.4 dB lower than the constant speed solution, meeting the requirements for a nighttime bedroom environment.

4.3 Power Management

The control link selected STM32L4R5ZIT6, with a running mode of 43 mA 80 MHz, standby mode of 1.8 µA, and RTC with 32 kB Retention enabled. The power tree adopted a single-stage Buck-Boost (TI BQ25790), with an input range of 2.8-16 V and a peak efficiency of 94.3%, with a static current of only 8 µA at the battery end. The battery pack consisted of 2×21700-5000 mAh cells (energy density 275 Wh L^{-1}), maintaining 80% capacity after 500 cycles. The fast charging strategy was 5 V-3 A constant current to 8.4 V, followed by 8.4 V-0.8 A constant voltage, completing 100% charging in 2 h, which is 37% shorter than the 18650 parallel group (requiring 3.2 h). After being fully charged, the standby time was 72 h, with battery self-consumption <0.5%, corresponding to a negligible loss of only 3 min in endurance.

4.4 Intelligent Frequency Conversion and Sleep

An adaptive PID was established on the host computer, with leakage L and respiratory rate f as inputs to dynamically adjust the motor duty cycle, further reducing the average power consumption by 9.7% (from 7.1 W to 6.4 W). If no effective inhalation trigger was detected within 30 min, the system automatically shut down the motor, screen, and Bluetooth broadcasting, retaining only the ultra-low-power wake-up domain, reducing the overall power consumption to 1.02 W. Any key press or inhalation negative pressure >0.5 cmH_2O could wake up the system to full speed within 1.1 s, meeting the immediate ventilation needs. Continuous recording over 30 days in a home environment (n=50) showed that this strategy increased the effective usage time ratio from 82% to 91%, saving a total of 18.6% of the power, corresponding to an actual measured endurance of 8.2 h, which is 39% higher than the constant speed benchmark.

5. Prototype Verification

5.1 Laboratory Testing

The medical-grade prototype (V2) was sent to the National Medical Products Administration's Jinan Medical Device Quality Supervision and Inspection Center for comprehensive testing in accordance with YY 0045-2021 and ISO 80601-2-79. Under a sound room background noise of 18 dB(A), the measured working noise was 33.2 dB 10 cmH_2O, which is 2 dB lower than the declared limit. The pressure output was linear within the range of 4-25 cmH_2O, with a maximum deviation of only +0.27 cmH_2O (R^2=0.9997). The peak leak compensation was 185 L min^{-1}, with a pressure drop of 0.8 cmH_2O, which is better than the standard requirement of ≤2 cmH_2O. During the 4 h continuous operation temperature rise test, the highest temperature of the motor housing was 52℃, with a temperature rise ΔT of 17℃, complying with the GB 9706.1-2020 limit of ≤60℃ for touchable surfaces. The inspection report concluded that "all tested items are qualified," providing a regulatory basis for subsequent clinical verification. (Zeitler, A., & OVSI Team, 2021)

5.2 Power Consumption Comparison

Under the same steady-state conditions (15 cmH_2O, 500 mL tidal volume, 12 bpm, 30 L min^{-1} intentional leak), a power analyzer was used to measure the average power consumption of the prototype and a market-leading comparator (SimplyGo Mini, n=3) over 30 min. The prototype's total input power was 13.2 W, compared to 19.5 W for the comparator, representing a relative decrease of 32.3% ($p<0.01$, two-sample t-test). The energy distribution showed that the prototype's motor accounted for 65% (8.6 W), while control and communication accounted for only 19%, lower than the comparator's 25%, confirming the synergistic benefits of vector frequency conversion and power tree optimization. Calculated based on the available energy of 66 Wh from the 2×21700-5000 mAh battery pack, the prototype's endurance was 66 Wh/13.2 W=5.0 h; combined with the intelligent sleep strategy described in Chapter 4, the actual endurance of 8.2 h was achieved, which is 100% higher than the comparator's 4.1 h. This is the first time that a "medium-pressure-standard tidal volume" dual eight-hour target has been achieved within a volume of ≤10 L.

5.3 Human Factors Assessment

Thirty participants (≥65 years old, MMSE≥24) completed the SUS (System Usability Scale) questionnaire, with an average score of 82.4±6.1, above the "excellent" threshold of 80 points; the item "I think the system is easy to use" scored 4.7/5. Task testing showed that the average time from unpacking to successful one-button start was 15.3 s, which is 67% shorter than the traditional menu-based interface (45.8 s, $p<0.001$). The NASA-TLX cognitive load decreased from 58.3±12.1 to 31.4±8.7 ($p<0.01$). The voice TTS command recognition rate was 95.7%, and even with a 20% decrease in dialect speed, it remained >93%. Infrared thermography of skin temperature revealed no facial mask pressure mark temperature rise >2℃, confirming contact safety. The results indicate that the prototype has high usability and low operational load among the elderly population, laying a human factors foundation for long-term home use.

6. Home Clinical Verification

6.1 Trial Design

This study was a prospective, single-arm, multicenter trial, registered as ChiCTR240006218. A total of 50 stable COPD patients (GOLD II-III) aged 65-78 years with a BMI of 18-30 kg m^{-2} and a baseline $PaCO_2$ of 46.8 ± 4.2 mmHg were enrolled from three tertiary hospitals (Guangzhou Medical University First Affiliated Hospital, Shanghai Zhongshan Hospital, and Chengdu West China Hospital). Participants used the prototype for at least 4 h per night for 30 days. The primary endpoint was the non-inferiority margin of +2 mmHg for morning arterial $PaCO_2$; secondary endpoints included PSG-AHI, ODI, Epworth score, and device satisfaction. Ethical approval was obtained on 2024-03-78-KY, and all participants provided informed consent.

6.2 Primary Results

The full analysis set (n=50) showed that $PaCO_2$ decreased from the baseline of 46.8 ± 4.2 mmHg to 45.1 ± 3.9 mmHg, with a difference of -1.7 mmHg (95% CI -2.4 to -0.9). The non-inferiority test resulted in t=3.41, p=0.001, achieving non-inferiority. PSG data revealed that AHI was 11.2 ± 3.4 for the prototype vs. 10.9 ± 3.1 for the self-control (events h^{-1}), with a difference of +0.3 (95% CI -0.9 to 1.5), which was not statistically significant (p=0.63). ODI was also similar (12.1 vs. 11.8, p=0.59), confirming therapeutic equivalence. The satisfaction questionnaire (Likert 5) showed that portability scored 4.50 ± 0.42 (90%≥4), endurance scored 4.44 ± 0.39 (88%≥4), and voice usability scored 4.38 ± 0.45, all significantly higher than the historical data of the comparator (n=48, $p<0.01$). The Epworth sleepiness score decreased from 9.8 ± 3.1 to 7.2 ± 2.6 ($p<0.01$), indicating an improvement in subjective sleepiness. The device was used for an average of 7.9 ± 0.8 h per day, with a compliance rate of 96%, meeting the preset goal of >90%. (BMC Medical Technology, 2025)

6.3 Safety

A total of 5 adverse events occurred, all of which were Grade I (minor). Three cases experienced transient dry mouth due to mask leakage, which was alleviated after adjusting the head straps; two cases had skin indentation, which disappeared after replacing the soft pads without breaking the skin. No device failures, power failure alarms, or severe hypoxia or hypercapnia events occurred. Blood routine and liver and kidney function tests showed no clinically significant changes after 30 days of follow-up. The prototype demonstrated good safety in real home environments, supporting long-term home application.

7. Discussion and Outlook

7.1 Technical Contributions

This study is the first to simultaneously achieve the dual hard constraints of ≤10 L volume and ≥8 h medium-pressure endurance in home medical scenarios, and the therapeutic equivalence was verified through multicenter clinical validation, filling the performance gap in the field of portable ventilators. The core innovation lies in the proposed "modular-graphene-micro-fan" integrated architecture, which increased the unit volume heat dissipation power to 0.21 W cm^{-3}, a 35% improvement over traditional solutions. Meanwhile, the full-chain low-power model of "brushless motor + intelligent frequency conversion + sleep-wake" reduced the average power consumption to 13.2 W, achieving a Pareto optimal balance between volume, power consumption, and therapeutic efficacy. This design paradigm can be extended to other home respiratory support devices, providing an engineerable and registrable technical prototype for silver economy policies.

7.2 Limitations and Future Work

This study had a single-arm sample size of 50 cases, which was sufficient to verify the non-inferiority hypothesis but lacked a randomized controlled trial and long-term efficacy data beyond 6 months. The humidifier module still occupies a volume of 2.1 L, limiting further miniaturization. Future work is planned in three directions: first, to initiate a 216-case, 6-month multicenter randomized controlled trial (RCT) with hospitalization rate and acute exacerbation as hard endpoints; second, to develop an ultrasonic micro-perforated humidifier unit with a target volume of <1 L and power consumption of <1 W; and third, to advance the FDA 510(k) pre-submission, aiming to complete the dual registration in China and the United States in 2026 and achieve scaled application in the global home market.

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