Majalah Ilmiah Fisioterapi Indonesia
Indonesian Scientific Journal of Physiotherapy

Original Research Articles
ISSN (Print): 2303-1921
ISSN (Online): 2722-0443
Volume 14, Number 1, Pages 46-53 (2026)
DOI: https://doi.org/10.24843/mifi.000001061

Flexible Tubing Modification of Jet Nebulizers in Supine Patients: A Crossover Pilot Trial

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Received 9 December 2025; Revised 25 December 2025; Accepted 27 December 2025; Published 2 January 2026

Abstract

Background: Jet nebulizers are widely used in patients with respiratory disorders such as chronic obstructive pulmonary disease, asthma, and pneumonia. Their effectiveness depends on maintaining the medication cup in an upright position, which limits use in supine patients or those unable to sit upright. This limitation often reduces comfort and treatment efficiency, indicating the need for a more flexible device design.

Objective: To develop a flexible tubing modification for a jet nebulizer and to evaluate its feasibility and preliminary effectiveness through expert judgment and an in vivo pilot crossover trial.

Methods: This study employed a Research and Development approach using the MANTAP model, followed by a randomized crossover pilot trial. Product feasibility was assessed through expert judgment involving pulmonologists, physiotherapists, and academic experts. Six hospitalized patients received both standard and modified jet nebulizer interventions in randomized order with a 48-hour washout period. Patient satisfaction was measured using the Patient Satisfaction and Preference Questionnaire, and nebulization duration was recorded. Data were analyzed using the Wilcoxon signed-rank test.

Results: Expert evaluation confirmed that the modified nebulizer was feasible for clinical use. Patient satisfaction was significantly higher with the modified device than with the standard nebulizer ($Z = -2.232$; $p = 0.026$). Nebulization duration was also significantly shorter with the modified design ($Z = -1.992$; $p = 0.046$).

Conclusion: The flexible tubing modification of a jet nebulizer improved patient satisfaction and reduced treatment duration compared with the standard design, demonstrating potential benefits for nebulization therapy in supine patients.

Keywords
Nebulizers and Vaporizers; Equipment Design; Patient Satisfaction; Inhalation Therapy

Introduction

Chronic respiratory diseases remain a major global health burden, with chronic obstructive pulmonary disease (COPD) ranked as the third leading cause of death worldwide. The global mortality attributable to COPD reached approximately 3.23 million deaths in 2019 and is projected to increase due to persistent exposure to air pollution and tobacco smoke. COPD is characterized by progressive and largely irreversible airflow limitation associated with chronic airway inflammation and structural changes in the respiratory tract. One of the most disabling symptoms experienced by patients with COPD and other obstructive lung diseases is dyspnea, which arises from increased work of breathing, airway narrowing, and reduced elastic recoil of the lungs.[1,2] This symptom significantly limits functional capacity and quality of life, particularly in hospitalized and immobilized patients.[3]

Inhalation therapy represents a cornerstone of respiratory management, enabling direct delivery of bronchodilators, mucolytics, and anti-inflammatory agents to the airways while minimizing systemic side effects. Nebulizers are commonly used inhalation devices, particularly in acute care settings and among patients who have difficulty coordinating inhaler use.[4] Nebulizers function by converting liquid medication into fine aerosol particles that can be inhaled into the lower respiratory tract.[5,6] Several types of nebulizers are currently available, including jet (compressor) nebulizers, ultrasonic nebulizers, and vibrating mesh nebulizers. Although mesh and ultrasonic nebulizers generally demonstrate higher aerosol delivery efficiency, jet nebulizers remain the most widely used in clinical practice due to their lower cost, ease of maintenance, and broad availability.[7,8]

Jet nebulizers operate by generating pressurized airflow that passes through a narrow orifice into a medication cup. The resulting negative pressure draws liquid medication upward, where it is fragmented by a baffle into aerosol particles with micrometer-scale diameters. These particles are then delivered to the patient through a mask or mouthpiece. Optimal aerosol generation in jet nebulizers requires the medication cup to remain in an upright position to ensure consistent contact between the liquid medication, airflow, and baffle.[4,9] Consequently, patients are typically instructed to sit upright or maintain a semi-recumbent position during nebulization. This requirement poses significant challenges for patients who are bedridden, critically ill, or unable to tolerate upright positioning.

In supine patients, the medication cup often tilts into a horizontal orientation, resulting in incomplete aerosolization of the liquid medication. Under these conditions, a substantial proportion of the drug fails to contact the baffle effectively, leading to reduced aerosol output, prolonged nebulization time, and suboptimal drug delivery.[10] Furthermore, healthcare providers frequently need to manually stabilize the nebulizer cup to maintain its vertical orientation, increasing physical workload and time demands, particularly in busy inpatient settings.[11,12] These limitations reduce both the efficiency and comfort of nebulization therapy for patients and clinicians alike.

Several previous studies have attempted to address these challenges through mechanical modifications of jet nebulizer systems. Proposed solutions have included the addition of angled connectors, catheter mounts, and swivel adapters to facilitate nebulization in the supine position. While these modifications have demonstrated feasibility, they introduce multiple angular junctions

that may increase airflow turbulence, promote aerosol condensation, and reduce effective drug delivery.[13,12] Moreover, increased circuit complexity may raise concerns regarding infection control, dead-space volume, and device safety.

Recent experimental and clinical studies have highlighted the importance of nebulizer positioning and circuit configuration in determining aerosol deposition efficiency. Modifications to tubing length and orientation have been shown to alter particle size distribution and regional lung deposition, in some cases doubling pulmonary drug delivery.[14,15] However, these benefits must be carefully balanced against the potential drawbacks of increased dead space, which may be particularly relevant in patients with low tidal volumes. Despite these considerations, there remains a lack of practical jet nebulizer modifications that allow comfortable use in the supine position without compromising treatment efficiency or patient safety.

Against this background, the present study aimed to develop a modified jet nebulizer design incorporating a flexible tubing segment positioned between the medication cup and the patient interface. This design was intended to maintain the medication cup in an optimal upright orientation while allowing greater positional flexibility for supine patients. In addition to technical feasibility, the study focused on patient-reported outcomes, particularly satisfaction and perceived comfort, as these factors play a critical role in treatment adherence and clinical effectiveness. The objective of this study was therefore to evaluate the feasibility and preliminary effectiveness of the modified jet nebulizer through expert judgment and an in vivo randomized crossover pilot trial in hospitalized patients.

Methods

Study Design

This study employed a combined Research and Development (R&D) approach followed by a randomized crossover pilot trial. The R&D phase aimed to design and validate a modified jet nebulizer suitable for use in supine patients, while the crossover pilot trial evaluated its preliminary feasibility and effectiveness in a clinical setting.[16,17] The crossover design was selected to minimize inter-individual variability by allowing each participant to serve as their own control, which is appropriate for early-stage pilot investigations of medical device modifications.[18,19,20]

Product Development and Device Description

Development Framework

The product development process followed the MANTAP model, which consists of five sequential stages: (1) preliminary research, (2) planning, (3) product development, (4) pilot product testing, and (5) dissemination. This model was selected to ensure a systematic approach to identifying clinical needs, designing the device, and evaluating its early clinical applicability.

Standard Jet Nebulizer Configuration

A conventional jet (compressor) nebulizer was used as the reference device. Jet nebulizers operate by generating pressurized airflow that passes through a narrow orifice into the medication cup, creating negative pressure that draws liquid medication upward. The liquid medication is fragmented by a baffle into aerosol particles, which are subsequently delivered to the patient via a face mask or mouthpiece. Optimal aerosol generation requires the medication cup to remain in an upright position to ensure consistent interaction between airflow, liquid medication, and the baffle. Figure 1 illustrates the working mechanism and standard configuration of a jet nebulizer, highlighting the dependence of aerosol generation on the vertical orientation of the medication cup.

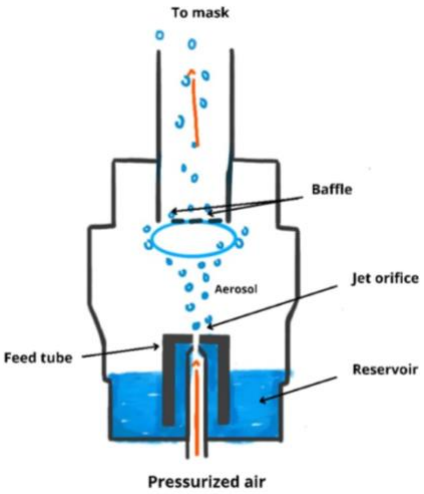

Figure 1. Schematic illustration of a standard jet nebulizer configuration.

Modified Jet Nebulizer Design

Based on findings from the preliminary research phase, a modified jet nebulizer design was developed to allow nebulization therapy in supine patients without compromising aerosol generation. The modification involved inserting a flexible breathing-circuit tubing segment between the medication cup and the patient interface (mask or mouthpiece). This configuration enabled the medication cup to remain in an upright position while allowing positional flexibility at the patient interface.

The flexible tubing used in the prototype had an internal diameter of approximately 29 mm and an adjustable length of up to 14 inches (35.5 cm). The tubing material was sufficiently elastic to permit bending and positional adjustment without kinking or obstructing aerosol flow. The modification was designed to minimize abrupt angular changes in airflow, thereby reducing turbulence and aerosol condensation compared with previously reported multi-angle connector designs. The final modified configuration is shown in Figure 2, demonstrating the spatial separation between the medication cup and the patient interface while preserving the functional orientation of the nebulizer cup.

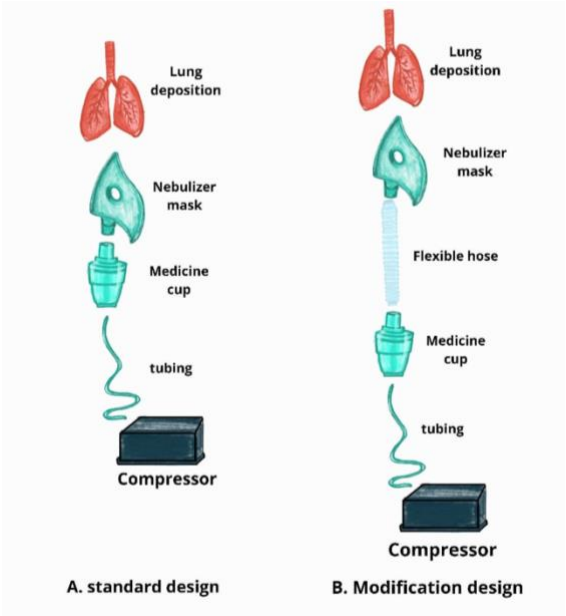

Figure 2. Modified jet nebulizer incorporating a flexible tubing segment between the medication cup and patient interface.

Expert Validation

The feasibility and safety of the modified nebulizer design were evaluated through expert judgment. Experts included a pulmonologist, an experienced cardiopulmonary physiotherapist, and academic physiotherapy staff with expertise in respiratory care and medical device evaluation. Each expert independently assessed the prototype using a structured questionnaire based on a 5-point Likert scale (1 = very poor to 5 = excellent), covering technical feasibility, functional performance, safety, ergonomic design, and potential clinical benefits.

Expert feedback emphasized the importance of secure connections, safe and durable materials, and maintenance of unobstructed aerosol flow. Based on these recommendations, minor revisions were made to improve connection stability and ensure compatibility with standard nebulizer components. The finalized prototype was subsequently used in the pilot clinical trial.

Pilot Study Procedure

Participants

The pilot study was conducted at Al-Huda Hospital, Banyuwangi, Indonesia. Six hospitalized adult patients were recruited using convenience sampling. Inclusion criteria were: (1) presence of respiratory disorders requiring nebulization therapy, (2) evidence of airway mucus, and (3) inability or difficulty maintaining an upright sitting position. Exclusion criteria included refusal to use the modified device and severe cognitive impairment that precluded informed consent or questionnaire completion.

Crossover Intervention Protocol

The clinical evaluation employed a randomized crossover design. Each participant received two interventions: nebulization using a standard jet nebulizer and nebulization using the modified jet nebulizer. The order of interventions was randomized using simple block randomization with a 1:1 allocation ratio (sequence AB or BA).

A 48-hour washout period was implemented between intervention periods to minimize pharmacological and perceptual carryover effects. During the washout period, participants continued to receive routine nebulization therapy as prescribed by the attending physician, administered twice daily at standardized times (08:00 and 16:00). This washout duration encompassed multiple dosing cycles and was intended to ensure physiological stabilization prior to the subsequent intervention period. The overall flow of participant enrollment, randomization, intervention, and outcome assessment is presented in Figure 3.

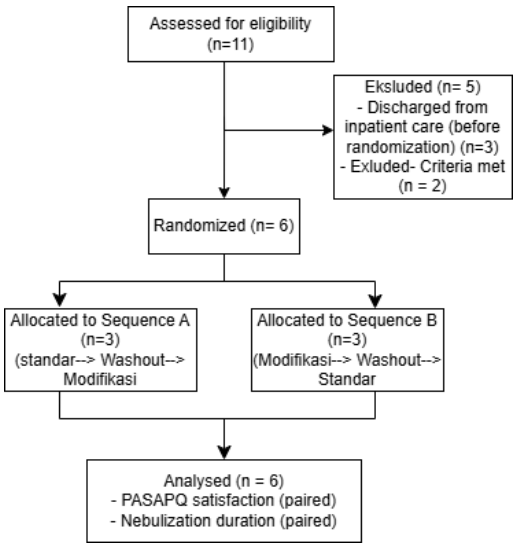

Figure 3. Study flowchart of the randomized crossover pilot trial.

Outcome Measures

Patient Satisfaction

Patient satisfaction and preference were assessed using the Patient Satisfaction and Preference Questionnaire (PASAPQ). The PASAPQ is a validated instrument with good internal consistency (Cronbach's $\alpha > 0.70$) and established construct validity. A validated Indonesian version was used, which had undergone forward–backward translation and pilot testing to ensure semantic equivalence. Total PASAPQ scores were used for analysis.

Nebulization Duration

Nebulization duration was measured using a stopwatch, recording the time from initiation of aerosol generation until the medication reservoir was empty. Measurements were performed by the researcher. Due to visible differences between devices, assessor blinding was not feasible and was acknowledged as a limitation.

Statistical Analysis

Statistical analyses were conducted using IBM SPSS Statistics version 20. Data distribution was assessed using the Shapiro–Wilk test. As outcome variables were not normally distributed, comparisons between standard and modified nebulizer conditions were performed using the Wilcoxon signed-rank test. Statistical significance was set at $\alpha = 0.05$, and effect sizes (r) were calculated to estimate the magnitude of observed differences.

Ethical Considerations

This study was approved by the Health Research Ethics Committee of the Faculty of Health Sciences, Universitas Muhammadiyah Surakarta (Ethical Approval No. 1242/KEPK-FIK/V/2025). All participants provided written informed consent prior to participation.

Results

Preliminary Research Findings

The preliminary research phase identified key practical challenges associated with the use of standard jet nebulizers in hospitalized patients. Interviews with physiotherapists at Al-Huda Hospital, Banyuwangi, revealed consistent difficulties when administering nebulization therapy to patients who were unable to maintain an upright sitting position. Physiotherapists reported the need to manually stabilize the medication cup to keep it vertical during therapy, particularly in supine patients, to ensure adequate aerosol generation. This requirement increased physical workload and time demands, especially in inpatient settings with high nebulization frequency. These findings supported the need for a device modification that would allow effective nebulization without requiring upright patient positioning.

Product Planning and Development Outcomes

During the planning stage, a modification concept involving the addition of a flexible tubing segment between the patient interface and the medication cup was selected based on feasibility, availability, and compatibility with existing jet nebulizer systems. A commercially available standard jet nebulizer mask (One-Health) and a flexible breathing circuit tubing (Gea) were used for the prototype. Initial assembly employed adjustable sealing tape to secure connections between components.

Expert judgment was conducted during the product development stage to assess feasibility, safety, functionality, and ergonomic design. Experts included a pulmonologist, an experienced cardiopulmonary physiotherapist, and academic physiotherapy staff with expertise in respiratory care. Evaluation covered technical performance, patient safety, material suitability, and clinical applicability. Expert feedback indicated that the modified design was feasible for clinical use, with recommendations emphasizing improved connection stability, safe materials, and adherence to medical device standards. Following revision, the final prototype consisted of a jet nebulizer with an added flexible tubing segment up to 14 inches (35.5 cm) in length and approximately 29 mm in internal diameter, positioned between the medication cup and the patient interface. The tubing material allowed positional adjustment without kinking or obstructing aerosol flow.

Participant Characteristics

Six hospitalized patients participated in the crossover pilot trial. Participants were allocated into two crossover sequences: Group A (standard nebulizer followed by modified nebulizer) and Group B (modified nebulizer followed by standard nebulizer), with three participants in each group.

Baseline characteristics are presented in Table 1. The age distribution ranged from 55 to 85 years. Group A had a lower mean age and included both male and female participants, whereas Group B had a higher mean age and consisted entirely of male participants. Although baseline differences between groups were observed, the crossover design ensured that each participant served as their own control, thereby reducing the influence of between-group variability.

Table 1. Baseline Characteristics of Participants by Crossover Sequence

Characteristic	Group A (n = 3) Standard → Modified	Group B (n = 3) Modified → Standard	Total (n = 6)
Age (years)			
55	1 (16.7%)	0	1 (16.7%)
70	1 (16.7%)	0	1 (16.7%)
78	1 (16.7%)	1 (16.7%)	2 (33.3%)
82	0	1 (16.7%)	1 (16.7%)
85	0	1 (16.7%)	1 (16.7%)
Sex			
Male	1 (16.7%)	3 (50.0%)	4 (66.7%)
Female	2 (33.3%)	0	2 (33.3%)
Mean age (SD), years	67.6 (11.6)	81.6 (3.5)	–

Footnote: Baseline imbalance between crossover sequences was observed; however, the crossover design allowed each participant to serve as their own control.

Normality Testing

Normality testing was conducted for both outcome variables—patient satisfaction and nebulization duration—using the Shapiro–Wilk test due to the small sample size (n = 6). Results demonstrated that data for both outcomes were not normally distributed under either intervention condition.

For patient satisfaction scores measured using the PASAPQ, Shapiro–Wilk test results indicated non-normal distribution for both the standard nebulizer and the modified nebulizer conditions ($p < 0.05$). Similarly, nebulization duration data for both devices were non-normally distributed. Consequently, non-parametric statistical analyses were applied for all comparative testing.

Patient Satisfaction Outcomes

Patient satisfaction scores assessed using the PASAPQ are summarized in Table 2. Median satisfaction scores were higher for the modified nebulizer compared with the standard nebulizer, with a narrower interquartile range observed for the modified device.

Table 2. Normality Test of Patient Satisfaction Scores (PASAPQ)

Device	Median (IQR)	Shapiro–Wilk Statistic	p-value	Effect Size (r)	Interpretation
Standard jet nebulizer	30.0 (2.75)	0.745	0.018	0.91	Large effect
Modified jet nebulizer	32.0 (2.50)	0.747	0.019	0.91	Large effect

Footnote: Non-normal distribution justified the use of non-parametric tests.

Wilcoxon signed-rank analysis demonstrated that all six participants exhibited higher satisfaction scores when using the modified nebulizer compared with the standard nebulizer (Table 3). No participants showed a decrease in satisfaction with the modified device. The Wilcoxon signed-rank test confirmed a statistically significant difference in satisfaction scores between the two conditions ($Z = -2.232$; $p = 0.026$), indicating greater patient satisfaction with the modified nebulizer (Table 4). The calculated effect size ($r = 0.91$) indicated a large effect magnitude.

Table 3. Wilcoxon Signed-Rank Test: Patient Satisfaction Ranks

Rank Category	n	Mean Rank	Sum of Ranks
Negative ranks (Modified < Standard)	0	0.00	0.00
Positive ranks (Modified > Standard)	6	3.50	21.00

Table 4. Wilcoxon Signed-Rank Test: Patient Satisfaction (PASAPQ)

Outcome Comparison	Z	p-value (2-tailed)
Modified vs. standard nebulizer	−2.232	0.026

Nebulization Duration Outcomes

Nebulization duration data are presented in Table 5. Median duration was shorter for the modified nebulizer compared with the standard nebulizer, although variability across participants was slightly greater in the modified condition, as reflected by a wider interquartile range.

Table 5. Normality Test of Nebulization Duration

Device	Median (IQR)	Shapiro–Wilk Statistic	p-value	Effect Size (r)	Interpretation
Standard jet nebulizer	7.34 (7.84)	0.760	0.025	0.81	Large effect
Modified jet nebulizer	6.49 (8.53)	0.721	0.010	0.81	Large effect

Wilcoxon signed-rank ranking results showed that five of the six participants experienced shorter nebulization durations when using the modified nebulizer, while one participant had a longer duration compared with the standard device (Table 6). Statistical testing confirmed a significant difference in nebulization duration between devices ($Z = -1.992$; $p = 0.046$), with shorter treatment times observed for the modified nebulizer (Table 7). The corresponding effect size ($r = 0.81$) also indicated a large effect magnitude.

Table 6. Wilcoxon Signed-Rank Test: Nebulization Duration Ranks

Rank Category	n	Mean Rank	Sum of Ranks
Negative ranks (Modified < Standard)	5	4.00	20.00
Positive ranks (Modified > Standard)	1	1.00	1.00

Table 7. Wilcoxon Signed-Rank Test: Nebulization Duration

Outcome Comparison	Z	p-value (2-tailed)
Modified vs. standard nebulizer	−1.992	0.046

Summary of Findings

Overall, the pilot crossover trial demonstrated that the modified jet nebulizer was associated with higher patient satisfaction and shorter nebulization duration compared with the standard jet nebulizer in hospitalized patients. These findings were consistent across participants and supported by large effect sizes for both outcomes.

Discussion

This study evaluated a flexible tubing modification of a jet nebulizer designed to facilitate nebulization therapy in supine hospitalized patients. The main findings of this crossover pilot trial were that the modified nebulizer resulted in significantly higher patient satisfaction and significantly shorter nebulization duration compared with the standard jet nebulizer. These results suggest that a relatively simple mechanical modification may improve the usability and perceived effectiveness of nebulization therapy in patients who are unable to maintain an upright position.

Efficient aerosol delivery in patients with acute or chronic respiratory disease depends on the complex interaction between aerosol particle characteristics, airway geometry, and patient breathing patterns. Aerosol deposition within the respiratory tract occurs primarily through inertial impaction, gravitational sedimentation, and diffusion, with particle size playing a central role in determining deposition site. Larger particles tend to deposit in the upper airways through impaction, whereas medium-sized particles are more

likely to reach the bronchi and bronchioles by sedimentation, and smaller particles may penetrate to the alveoli by diffusion. In patients with obstructive lung disease, airflow limitation and turbulence further complicate these mechanisms, often leading to premature central airway deposition and reduced peripheral drug delivery.[21,22,23]

Standard jet nebulizers are particularly sensitive to device orientation because optimal aerosol generation requires the medication cup to remain upright. In supine patients, tilting of the medication cup disrupts the interaction between pressurized airflow, liquid medication, and the baffle, resulting in incomplete aerosolization and prolonged nebulization time. This limitation has been consistently reported in clinical practice and previous studies, where healthcare providers are often required to manually stabilize the nebulizer to maintain adequate performance.[13,24] The flexible tubing modification evaluated in this study was designed to address this fundamental mechanical constraint by decoupling the orientation of the medication cup from the patient interface.

The observed increase in patient satisfaction with the modified nebulizer likely reflects improved comfort and ease of use. By allowing the medication cup to remain upright while the patient remained supine, the modified design reduced the need for frequent repositioning of the device or the patient. This improvement is particularly relevant for hospitalized patients with limited mobility, fatigue, or severe dyspnea, for whom maintaining an upright position may exacerbate respiratory distress. Patient-reported outcomes, such as satisfaction and comfort, are increasingly recognized as critical indicators of intervention success, as they influence adherence, tolerance, and overall therapeutic effectiveness.

In addition to improved satisfaction, the modified nebulizer was associated with a significantly shorter nebulization duration. Several mechanisms may explain this finding. First, maintaining the medication cup in an optimal orientation likely improved aerosol generation efficiency, allowing more consistent atomization of the liquid medication and reducing residual volume within the cup. Second, the flexible tubing may have acted as a short aerosol reservoir. During expiration, aerosol particles accumulated within the tubing and were subsequently inhaled during the next inspiratory phase, thereby improving delivery efficiency without prolonging treatment time. This reservoir effect has been described in previous aerosol delivery studies, particularly in mechanically ventilated patients.[23,25,24]

The addition of flexible tubing inevitably increased circuit dead space. Quantitative estimation indicated that, at an average tubing length of approximately 20 cm, the added dead space was around 132 mL, corresponding to roughly one quarter of the average adult tidal volume. Although increased dead space raises theoretical concerns regarding carbon dioxide rebreathing, this risk was mitigated in the present study by the use of an open-face mask with expiratory ports, allowing exhaled gases to escape. Moreover, the observed reduction in nebulization duration suggests that the additional dead space did not adversely affect overall treatment efficiency in this pilot sample. Instead, the increased internal volume may have contributed to smoother aerosol flow and reduced turbulence at the patient interface.

These findings are consistent with previous reports emphasizing that nebulizer configuration and circuit design can substantially influence aerosol delivery efficiency. Prior studies that introduced angled connectors or swivel adapters for supine nebulization demonstrated feasibility but raised concerns regarding turbulence and aerosol condensation at multiple junctions.[12,13] In contrast, the current modification used a single flexible tubing segment with a smooth curvature, potentially reducing abrupt directional changes and minimizing aerosol loss. This simpler configuration may offer a practical advantage in routine clinical settings.

The crossover design of this study strengthened internal validity by allowing each participant to serve as their own control, thereby reducing the impact of inter-individual variability in disease severity, breathing pattern, and subjective perception. The 48-hour washout period was selected to minimize pharmacological and perceptual carryover effects while maintaining ethical standards by allowing continued routine nebulization therapy. The washout duration encompassed multiple dosing cycles, supporting physiological stabilization prior to the second intervention. Nevertheless, residual carryover effects and period effects cannot be entirely excluded, particularly given the subjective nature of the satisfaction outcome.

Several limitations should be acknowledged. First, this was a small pilot study involving only six participants at a single center, which limits generalizability. The study was not powered to detect small effect sizes or to evaluate clinical outcomes such as lung function, oxygenation, or symptom severity. Second, outcome assessment focused primarily on patient-reported satisfaction and treatment duration, without objective measures of aerosol deposition or clinical efficacy. Third, blinding of participants and assessors was not feasible due to the visible differences between devices, introducing potential observation and reporting bias. Finally, the prototype connections used sealing tape rather than standardized medical-grade connectors, which may affect durability and infection control considerations in routine use.

Despite these limitations, the findings provide preliminary evidence that a simple mechanical modification to a jet nebulizer can improve patient experience and procedural efficiency in supine patients. From a clinical perspective, improved comfort and shorter treatment duration may enhance adherence to inhalation therapy, reduce staff workload, and support continuity of respiratory care in hospitalized and immobilized patients. These benefits are particularly relevant in resource-limited settings where jet nebulizers remain the primary inhalation device due to cost and availability.

Future research should build on these findings by conducting larger, adequately powered randomized trials incorporating objective outcome measures such as aerosol output, lung deposition, gas exchange, and clinical symptom scores. In vitro testing and computational fluid dynamics analyses would also be valuable to further characterize airflow patterns, particle behavior, and dead-space effects associated with the modified design. Additionally, the use of standardized medical-grade connectors and materials should be evaluated to ensure long-term safety, hygiene, and regulatory compliance.

Conclusion

This study demonstrated that a flexible tubing modification of a jet nebulizer can improve the delivery of nebulization therapy in hospitalized patients who are unable to maintain an upright position. In this randomized crossover pilot trial, the modified nebulizer was associated with significantly higher patient satisfaction and a significantly shorter nebulization duration compared with the standard jet nebulizer. These findings indicate that the modification enhanced both the perceived comfort and procedural efficiency of inhalation therapy without compromising usability in supine patients.

From a clinical perspective, maintaining the medication cup in an optimal upright orientation while allowing positional flexibility appears to address a key mechanical limitation of conventional jet nebulizers. Improved comfort and ease of use may support better patient tolerance and adherence to nebulization therapy, particularly in patients with limited mobility, fatigue, or severe respiratory symptoms. The observed reduction in treatment duration also suggests potential benefits in workflow efficiency for healthcare providers in inpatient settings.

However, the findings of this study should be interpreted with caution. The small sample size, single-center setting, and reliance on patient-reported outcomes limit the generalizability of the results. Furthermore, objective clinical outcomes such as lung

function, aerosol deposition, and gas exchange were not assessed. The prototype device also requires further refinement using standardized medical-grade connectors and materials to ensure safety, durability, and compliance with regulatory standards.

In conclusion, the flexible tubing modification of a jet nebulizer shows promising preliminary benefits for nebulization therapy in supine patients. Further in vitro testing and larger, well-powered clinical trials incorporating objective outcome measures are necessary before widespread clinical implementation can be recommended.

Author Contribution

Conceptualization: Zahrina Alyani Firdaus, Isnaini Herawati
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Writing—review & editing: Isnaini Herawati
Supervision: Isnaini Herawati

Acknowledgments

The authors would like to express their sincere gratitude to all individuals who contributed to the completion of this study. Special thanks are extended to the expert validators for their valuable assessments and constructive feedback during the product development phase. The authors also thank the physiotherapy staff at Al-Huda Hospital, Banyuwangi, for their assistance and support during data collection, as well as all patients who generously participated in this study. Their cooperation and willingness to contribute were essential to the successful implementation of the research.

Conflict of Interest Statement

The authors declare that there is no conflict of interest related to this study.

Funding Sources

This research received no external funding.

Ethics Statement

This study was conducted in accordance with the principles of research ethics, including voluntary participation and written informed consent from all participants. Confidentiality of participant data was strictly maintained and data were used solely for research purposes. Ethical approval was granted by the Health Research Ethics Committee of the Faculty of Health Sciences, Universitas Muhammadiyah Surakarta (Ethical Approval No. 1242/KEPK-FIK/V/2025).

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