Design and Development of Compact Portable Mesh Nebulizer Based on Customer Needs and 3D Printing Technology

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Abstract. Aerosol therapy is a modern method of instrumental therapy that aims to deliver medication to the patient's respiratory tract in the form of an inhaled aerosol. Nebulizers are the oldest form of aerosol generation. Although they have been in common use for many years, their fundamental design and performance have changed little over the past 25 years. The development of mesh nebulizer technology has expanded the ability to deliver medical aerosols to infants and young children via nasal cannula and tubing. Benchmarking analysis identified several critical deficiencies in existing portable mesh nebulizer designs, particularly related to ergonomic handling and aesthetics. This study aimed to develop a design with a stronger and more durable outer frame, which is ergonomically comfortable to hold and visually appealing, to improve the user experience and increase the appeal of this medical device. The methodology in this study was based on the Karl Ulrich product design and development method. Seven design concepts were created using CAD and the prototyping process used 3D printing from PLA.

Keywords: Mesh Nebulizer, Ergonomic Medical Device, Product Design, 3D Printing, Portable Medical Device.

1 Introduction

Respiratory diseases such as asthma and chronic obstructive pulmonary dis-ease (COPD) remain leading causes of morbidity globally. Aerosol therapy has become a widely accepted approach for delivering medications directly to the respiratory tract due to its ability to enhance drug deposition in the lungs (New-man & Gee-Turner, 2005). Over the past decades, nebulizer technology has ad-vanced significantly—from large, noisy jet nebulizers to compact mesh nebuliz-ers capable of producing fine aerosol particles more efficiently (Faarc, 2000).

Among the three primary types of nebulizers jet, ultrasonic, and mesh nebuliz-ers are increasingly favored for their low power consumption, portability, and ability to

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generate consistent particle sizes without inducing thermal degradation of sensitive drugs (Ari, 2014). Their design allows for tidal breathing, making them suitable for a broad range of users, including children and elderly patients with limited inspiratory capacity (Ari, Rubin, & Fink, 2022).

However, despite their technical advantages, many commercially available mesh nebulizers suffer from notable ergonomic and structural shortcomings. Benchmarking analyses of existing devices such as the Onemed M102, NB06, and Dr. Isla N6 highlight common issues including fragile casing, inadequate grip design, and lack of visual appeal. These limitations may compromise usability, especially for patients requiring frequent or prolonged therapy sessions.

As medical devices directly interact with users, design elements such as form factor, comfort, and interface clarity are critical to ensuring user safety, satisfac-tion, and compliance (Bitkina, Kim, & Park, 2020). Ergonomic principles, when effectively integrated, can enhance user experience and reduce operational er-rors. Furthermore, recent literature emphasizes the importance of incorporating user feedback early in the design process to increase product acceptability (Ul-rich & Eppinger, 2016).

In response to these challenges, this study adopts a user-centered design (UCD) approach to develop a compact portable mesh nebulizer that aligns with the ergonomic, aesthetic, and functional expectations of end-users. The development process is guided by Ulrich and Eppinger's product design methodology, which provides a structured framework encompassing customer need identification, target specification, concept generation and selection, and prototype testing (Ciurana, 2014).

Table 1. Deficiencies in Existing Products.

Existing Product	Deficiencies of the Frame / Casing
Onemed Nebulizer	• The casing structure is relatively thin. • Prone to breaking if dropped • The plastic material is quite stiff, not friendly for ergonomic grip • Slippery surface (glossy), risk of slipping when held.
NB06 Porta-ble Mesh Nebu-lizer	• The casing dimensions are quite large. • Less than optimal for mobility (less compact). • No anti-slip features or grip texture. • The durability of the casing material is low during drop testing.
Dr. Isla Nebulizer Handheld Port-able	• Slightly stiff design. • Slippery surface, prone to falling from grip. • Small button area, less ergonomic for elderly users. • High fragility at the joints between casing components.

Table 1 summarizes the key limitations identified in existing commercial portable nebulizers based on benchmarking analysis. By leveraging 3D printing (additive manufacturing) with PLA materials, the proposed design aims to combine rapid prototyping with environmentally conscious material selection (Ramani, 2018). This study contributes to the ongoing effort to produce medical devices that are not only clinically effective but also comfortable, safe, and visually appealing for everyday use.

1.1 Definition of Ergonomics in Product Design

Ergonomics represents a fundamental element in the design of medical devices, including nebulizers, as it directly relates to patient comfort, safety, and operational efficiency (Bitkina et al., 2020). An ergonomic design helps reduce both cognitive and physical load, accelerates user adaptation, and enhances adherence to respiratory therapy, particularly among patients with limited mobility or children.

The ergonomic design of medical devices should reference the principles outlined in SNI ISO 6385:2016, which describes the fundamental guidelines for adapting work system design to human capabilities. Additionally, IEC 62366 emphasizes the importance of applying usability engineering in the design of medical devices to ensure safety, effectiveness, and user comfort during device interaction.

In the context of mesh nebulizer design, ergonomic aspects can be further elaborated into several key design elements as follows:

a. Grip Form
   The grip design must consider the average hand shape of Indonesian users, with contour preferences that follow the anatomy of the thumb and index finger. According to the anthropometric study by Pheasant and Haslegrave (2018), the average adult hand width ranges from 75–95 mm. Therefore, the device surface was designed to be slightly curved and narrowed in the middle section to accommodate a natural grip when held single-handedly.
b. Device Weight
   The ideal weight of a portable device is ≤200 grams to enable one-handed use for more than five minutes without causing muscle fatigue. The final product developed in this study weighs approximately 180 grams (including the battery and electronic components), which remains within the acceptable user comfort range, as described by Wu et al. (2017) in their study of handheld medical devices.
c. Operational Button Placement
   The ON/OFF button and other controls are strategically positioned within reach of the thumb or index finger when the device is held, at an inclination angle of 30–45 degrees from the device's vertical axis. This arrangement is based on the "natural reach" ergonomic principle outlined by Kroemer and Grandjean (1997), emphasizing the importance of placing controls within the natural reach zone of the hand. This design minimizes the need to adjust the grip position, accelerates activation, and reduces the risk of accidental operation. This approach aligns with the usability engineering principles of IEC 62366-

1:2015, which recommend positioning critical controls in intuitive, easily accessible locations without interrupting therapy flow.

d. Viewing angle during use
   The device design considers the user's visual orientation during therapy. The display or indicators are placed at an elevation angle of 15–20 degrees from the horizontal axis to facilitate visibility when the device is used in a seated or reclining position. This approach refers to the optimal line-of-sight principles in human-computer interaction (HCI) design, as described by Zhang et al. (2020).
e. Average hand size and dimensional implications
   The device dimensions were adapted to the average adult Indonesian hand size, with an approximate hand length of 17–19 cm and palm width of 7–9 cm (Sumarni et al., 2017). Considering this range, the final nebulizer design features an overall length of approximately 13 cm and a grip circumference of 7.5 cm, making it suitable for both adults and adolescents without compromising grip stability.
   The ergonomic design implemented in this prototype not only provides physical comfort but also supports a comprehensive user experience, including a sense of safety and control during operation. This approach is consistent with IEC 62366 recommendations on usability engineering for medical devices, which emphasize that human-device interactions should minimize the potential for user error and enhance user confidence.

1.2 Design Standards

The reference standards applied in the product design process are as follows:

1. ISO 6385:2016 (en) Ergonomics Principles in the Design of Work Systems
2. IEC 62366 – Medical Devices – Application of Usability Engineering

2 Methodology

This study follows a structured product development framework adapted from Ulrich and Eppinger, emphasizing user-centered design principles. The methodology involves several key stages: identifying user needs, establishing target specifications, generating design concepts, evaluating and selecting concepts, and finally, developing a physical prototype using additive manufacturing.

2.1 User or Customer's Needs Identification

Customers are one of the key sources for new product development projects, and understanding customer needs is required to ensure product success (Majava, Nuottila, Haapasalo, & Law, 2014). An online questionnaire was distributed to 76 participants, comprising patients with chronic respiratory illnesses, caregivers, and healthcare practitioners. The survey consisted of both open- and close-ended questions regarding the

usability, portability, ergonomic comfort, maintenance, aesthetics, and functional expectations of portable nebulizers. The data were analyzed to extract common patterns of preferences, which were organized into a hierarchical list of needs, each rated based on importance using a 1–5 Likert scale.

2.2 Establishing Target Specification

Once the target specifications for the product have been set, they will drive the remaining of the product development effort. Consequently, if they don't properly capture what the customers and other relevant stakeholders are expecting from the product, it is very unlikely that the final design obtained at the end of the development process will be a success (Muci-Küchler, Weaver, & Dolan, 2007). Based on the interpreted user needs, a list of product specifications was formulated. These specifications included measurable criteria such as maximum device dimensions (< 67x48x125 mm), weight (< 150 g), battery life (> 60 minutes), ease of grip (subjective ergonomic score ≥ 4), and aesthetic appeal. Each specification was assigned both marginal and ideal values to guide the design trade-offs.

2.3 Concept Generation

Concept is defined as that which refers to the figure of an object, along with other representations such as attributes or functions of the object, which existed, is existing, or might exist in the human mind as well as in the real world. concept generation as the process of composing a desirable concept towards the future. This definition aims at developing a framework in which the concept generation can be structured in an interdisciplinary manner, while focusing on our view. Concept is defined as that which refers to the figure of an object, along with other representations such as attributes or functions of the object, which existed, is existing, or might exist in the human mind as well as in the real world. concept generation as the process of composing a desirable concept towards the future. This definition aims at developing a framework in which the concept generation can be structured in an interdisciplinary manner, while focusing on our view (Taura & Nagai, 2013). Seven initial concepts were generated using SOLIDWORKS Education 2023 based on the established specifications. These concepts varied in geometry, interface layout, and component integration. Feedback sessions were held with engineering colleagues and potential users to evaluate visual appeal, perceived ease of use, and comfort.

2.4 Concept Selection and Testing

Concept selection is the process of evaluating concepts with respect to cus-tomer needs and other criteria, comparing the relative strengths and weaknesses of the concepts, and selecting one or more concepts for further investigation or development (Ulrich & Eppinger, 2016).

A concept test solicits a direct response to a description of the product concept from potential customers in the target market. Pengujian konsep dapat memveri-fikasi bahwa

kebutuhan pelanggan telah dipenuhi secara memadai oleh konsep produk, menilai potensi penjualan konsep produk, dan/atau mengumpulkan in-formasi pelanggan untuk menyempurnakan konsep produk (Ulrich & Eppinger, 2016).

The revised design concepts were evaluated by 78 respondents using a struc-tured Likert-scale assessment on attributes such as comfort, usability, and ap-pearance. The concept receiving the highest total score (Concept 2) was selected for prototyping.

2.5 Prototyping

Product development almost always requires the building and testing of proto-types. A prototype is an approximation of the product on one or more dimensions of interest (Ulrich & Eppinger, 2016). 3D printing technology was called rapid prototype technology and has been well applied in a variety of industries with different printing techniques and materials (Fan et al., 2020). Additive manufac-turing (AM), commonly known as 3D printing, is a promising group of techniques for the quick and precise design of various types of products with complex ge-ometries (Oleksy, Dynarowicz, & Aebisher, 2023).

2.6 Evaluation and Positioning

The final prototype was assessed both qualitatively and quantitatively. Objective measurements (size, weight, battery duration) were compared against specifications and existing products. A positioning matrix was created to visually depict the prototype's standing relative to commercial benchmarks.

3 Result and Discussion

Table 2. Consumen needs and degrees of importance

No	Needs	Importance level
1.	Size and portability (easy to carry)	5
2.	Ergonomic design	5
3.	Aesthetic design	4
4.	Status indicators (battery, mode, etc.)	5
5.	Easy to clean and maintenance	5
6.	Ease of operation	5
7.	Safety of use (not easy to heat)	5
8.	Tool’s weight	5
9.	Compatibility with common liquid drugs	5
10.	Battery Life	5

Table 2 shows 10 points of consumen needs and the level of importance measured with numbers 1 to 5 with the following description:
1 = Not Important
2 = Less Important
3 = Important Enough
4 = Important
5 = Very Important

3.1 User Needs Identification

Table 3. Establishing target specifications

Needs	Metric	Unit/scale	Ideal Criteria
Size and portability (easy to carry)	Total dimensions (length × width × height)	Mm	≤ 120 × 70 × 40 mm
	Total volume	cm3	≤ 300 cm3
Ergonomic design	Grip comfort score (user testing)	Likert Scale 1–5	≥ 4
Aesthetic design	Visual design score (user survey)	Likert Scale 1–5	≥ 4
Status indicators	Number of active indicators (battery, mode, etc.)	Count	≥ 3 indicators
	Indicator visibility in low light	Yes/No.	Yes
Easy to clean and maintain	Average cleaning time	Minutes	≤ 2 minutes
	Number of components to be cleaned	Count	≤ 3 components
Ease of operation	Time to start nebulization after activation	Seconds	≤ 10 seconds
	Ease-of-use score (user testing)	Likert Scale 1–5	≥ 4
Safety of use	Maximum surface temperature during operation	°C	≤ 40 °C
Tool's weight	Device weight	Grams	≤ 150 g
Compatibility with common liquid drugs	Percentage of compatible liquid drugs (e.g., saline, bronchodilators, corticosteroids, etc.)	%	≥ 90%
Battery Life	Duration of use per full charge	Minutes	≥ 120 minutes
	Time required for full battery charge	Hours	≤ 2 hours

The initial stage involved the collection and analysis of user preferences through a structured online survey administered to 76 participants. Table 2 presents the ten key needs identified, highlighting the critical importance attributed to portability,

ergonomic handling, and ease of use. Notably, over 80% of respondents rated ergonomic grip and compact dimensions as top priorities, confirming the necessity of redesigning form factors compared to existing devices. Table 3 present the needs, metrics, scales and ideal criterartions of target specifications.

3.2 Target Specification

To fulfill the set specifications depending on the details of the product concept that is ultimately chosen. For this reason, the initial specification is labeled "tar-get specification". In translating the user's needs into a set of specification values, the first step that needs to be done is to create metrics. To get metrics is to observe user needs one by one, then estimate the precise and measurable characteristics of a product that satisfies consumers (Ulrich & Eppinger, 2016).

3.3 Concept Generation

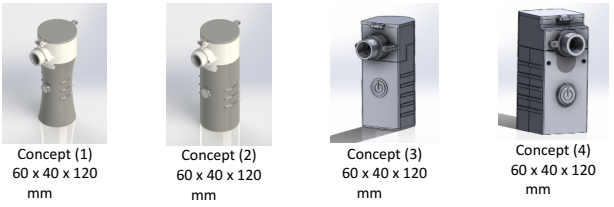

Fig.1. Product Concept Design 1

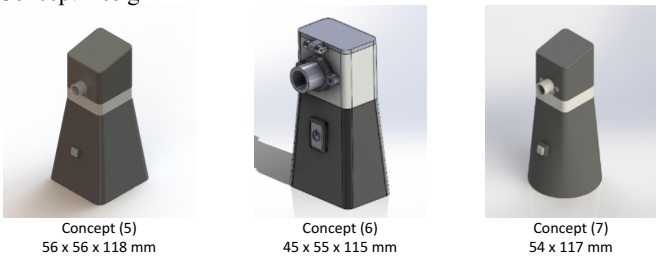

Fig.2. Product Concept Design 2

Figure 1 and 2 illustrate the second product concept generated during the ideation process, which incorporates ergonomic considerations and user handling preferences. Nowadays medical devices are a fast-growing industry. Advances in design, materials and technologies have increased the potential to find better solutions for those medical problems whose remedies were, up until now, unimaginable (Ciurana, 2014). Design is the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective (Freddi & Salmon, 2019).

The design for this research has been drawn using SOLIDWORKS Education 2023, It was one of the first 3D CAD (computer-aided design) applications designed to run on a desktop PC. Design and development used to be the first of the four product lifecycle (PLC) stages. This step is where ideas are transformed into definitions, which are then followed by geometrical shapes later on (Ciurana, 2014). Ergonomics (human factors) is the scientific discipline concerned with understanding the interactions between humans and other elements of a system and the application of theory, principles, data, and methods to design for optimising human well-being and overall system performance. The ergonomic design of equipment and environments is primarily based on the characteristics of the operation/user group and the optimisation of equipment and environment for operation and use by such groups to minimise human error and improve work efficiency, safety, and comfort (Li et al., 2021).

After identifying the customer needs and defining product metrics, and having established the initial specifications based on existing products and user re-quirements, the next stage is to generate several design concepts. These design concepts are developed based on the defined metrics and targeted specifications. The design concept model was developed based on the model of the existing nebulizer product that was benchmarked in this study, they are: Mesh Nebulizer Onemed M102, NB06 Portable Mesh Nebulizer and Dr. Isla Nebulizer (Handheld Mesh Type). Based on the analysis of competitor products and benchmarks on the 3 existing products that have been described earlier, several designs were made as shown below.

To create a unique design of a nebulizer, the design was also developed into several design models as follows.

3.4 Design Selection and User Testing

The seven alternative concept designs developed during the conceptual stage are presented in Figure 3 for comparison. The refined designs were evaluated by 78 respondents. Each participant was asked to score concept designs on a Likert scale (1–5) across five dimensions: portability, ergonomics, aesthetic appeal, ease of operation, and perceived durability. Table 3 summarizes the results, with Concept 2 achieving the highest total score across all attributes.

This selection process demonstrates a clear linkage between initial user needs and final design decisions. Respondents specifically highlighted the reduced overall volume, more pronounced grip indentations, and simplified interface as decisive factors in their preferences.

The results of the survey to 78 nebulizer users, produced a score for each design concept. After calculating one by one the design concepts, the final assessment results were obtained as follows.

Figure 4 shows the selected design concept that was chosen based on the evaluation criteria and user priority scoring. Based on the survey results of 78 mesh nebulizer users, the highest score was obtained for the second design concept. Therefore, design concept 2 was chosen because it received the highest score from users.

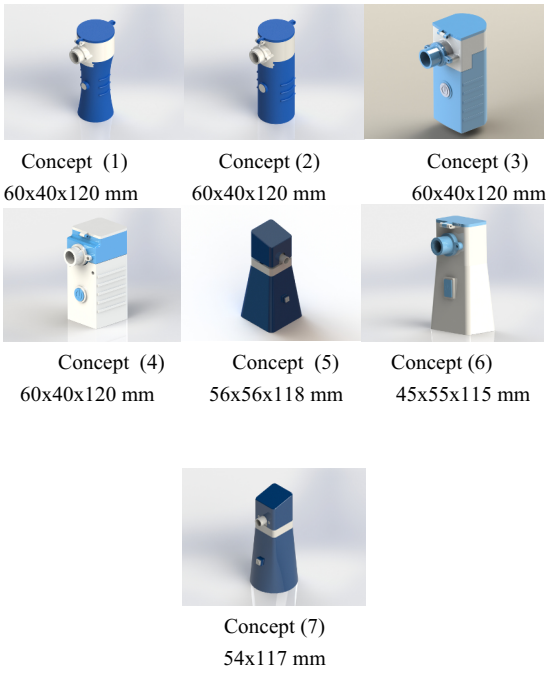

Fig.3. Seven Concept Designs

Table 4. Total score and selected designs

Concept Design	Total Score	Ranking
1	273.3	3
2	320.5	1
3	247.1	4
4	234.8	6
5	226.8	7
6	237.1	5
7	305.6	2

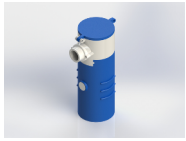

Fig.4. Selected Concept Design

3.5 Material Selection

In recent years, particularly in the design of high-frequency high-density elec-tronic equipment, use of plastics is becoming more common. Plastic materials give obvious advantages of lighter weight, ease of assembly, more aesthetic de-sign options, ease of processing, and cost-effectiveness (Ramani, 2018). Additive manufacturing (AM) is defined as the process of joining materials to make parts based on computer-generated 3D model data, usually layer upon layer, as op-posed to subtractive manufacturing and formative manufacturing methodologies (Karayannis, Petrakli, Gkika, & Koumoulos, 2019). Polylactic acid (PLA) is an aliphatic polyester produced as a racemic mixture of D and Llactide from non-toxic renewable sources, such as corn and sugarcane, with valuable properties for the biomedical field. Polylactic acid (PLA) has become one of the most common-ly used polymers in medical devices given its biocompatible, biode-gradable and bioabsorbable properties. In addition, due to PLA's thermoplastic behav-iour, these medical devices are now obtained using 3D printing tech nologies. Once obtained, the 3D-printed PLA devices undergo different sterilisation procedures, which are essential to prevent infections (Pérez-Davila et al., 2022). Then PLA material was used in the manufacture of this design prototype.

3.6 Prototyping

The selected design was prototyped using 3D printing (Creality Ender 3) with PLA filament due to its durability, biocompatibility, and ease of fabrication. The printing process was conducted at the Fabrication Lab, Department of Architecture, Universitas Indonesia. The prototype was assembled with standard nebulizer components (piezoelectric sensor, PCB, lithium battery, casing).

During the additive manufacturing stage, two design concepts (Concept 2 and Concept 7) were fabricated using 3D printing techniques. This consideration was made since Concept 7 also achieved a cumulative score exceeding 300 points. Figure 5 show the additive manufacturing workflow for fabricating the device housing and structural components.

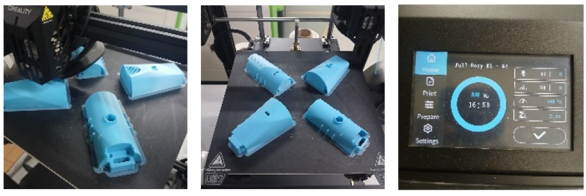

Fig.5. 3D Printing Process

3.7 Working Prototype

The working prototype utilized components sourced from the Dr. Isla nebulizer (used as a benchmark product) along with a lithium-ion battery. The selection of a lithium-

ion battery was based on its superior durability, extended operational lifespan, and the capability for repeated recharging.

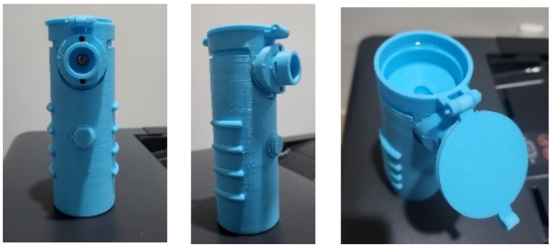

Fig.6. Working Prototype (off mode)

Figure 6 presents the physical prototype in an inactive mode to illustrate the external form and assembly configuration. The image above shows the results of prototyping using PLA filament. In these photos, the on/off button is not active, so aerosol vapor does not exit the front hole of the nebulizer. The top of the nebulizer is filled with water (when used, the water should be mixed with liquid medication specifically for respiratory ailments).

Fig.7. Working Prototype (on mode)

The operational state of the prototype is shown in Figure 7, demonstrating the device during nebulization. When the on button is activated, the PCB will be active so that the green light comes on and the water at the top of the nebulizer starts to evaporate via piezoelectricity.

Fig.8. Frame and PCB of Dr.Isla portable nebulizer Model-N6

Figure 8 illustrate the internal frame and electronic control board used as benchmarking reference. The Working prototype using components from the Dr.isla nebulizer (product benchmarking). In this experiment, the PCB of Dr.Isla portable nebulizer Model-N6 was used because its size matched the prototype that had been made.

Fig.9. Lithium Ion Battery

Figure 9 displays the lithium-ion battery module used as the primary power supply for the portable nebulizer. The use of lithium ion batteries was chosen because they are more durable and can be used for a long period of time and can be recharged.

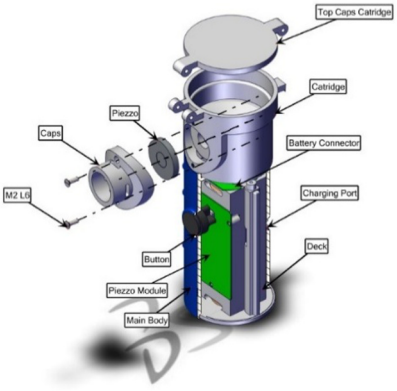

Fig.10. Anatomy of Components (front view)

The front-view component anatomy and spatial configuration are depicted in Figure 10. The image above is an image of the nebulizer components which consist of: Top Caps Catridge, Catridge, Battery Connector, Charging Port, Deck, Main Body, Piezzo Module, Button, Caps, Piezzo, screw M2 L6.

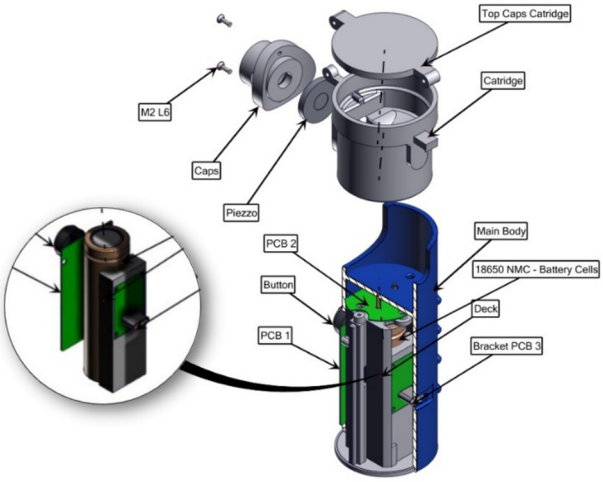

Fig.11. Anatomy of Components (side view)

Figure 11 provides a side view of the internal structural arrangement. The image above is a side view of the nebulizer components as described above.

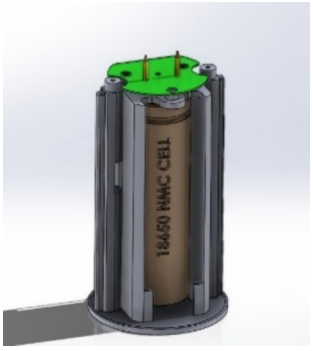

Fig.12. Battery Position

Figure 12 illustrates the placement of the battery relative to the PCB to ensure compact internal arrangement.

3.8 Comparative analysis with benchmark products

Table 5 provides a consolidated summary comparing the prototype with benchmark devices. While the final design achieved superior ergonomics and weight reduction, it remained cost-competitive by eliminating non-essential display modules and optimizing the casing geometry for additive manufacturing.

The combination of low-cost production and improved usability presents a compelling value proposition for small-scale clinical applications or home use scenarios.

Table 5. Comparative Analysis of Products Based on Benchmarking

Criteria	Onemed M102	NB06 Nebulizer	Dr. Isla N6	Final Design Product
Dimensions (L × W × H, mm)	120 × 65 × 40	110 × 60 × 55	125 × 58 × 50	130 × 55 × 40
Total Weight (grams)	190	200	210	180
Grip Ergonomics	Moderately comfortable	Comfortable	Comfortable	Very comfortable
Operational Button Position	On top of the device	On the side	Near the thumb	Near the thumb
Power Consumption	3.0 W	3.5 W	2.7 W	2.7 W
Battery Type	AAA (2 units)	A2 Rechargeable	A2 Rechargeable	Li-ion 2235 mAh Rechargeable

3.9 Quantification of Criteria Based on Respondent Feedback

The questionnaire results collected from 78 respondents regarding the final product design were analyzed using a 1–5 Likert scale across three main aspects: ergonomics, aesthetics, and casing strength. The outcomes are presented in Table 6.

Table 6. Respondent Evaluation Scores for the Product Design

Criteria	Average Score	Interpretation
Ergonomics	4.6	Very Good
Aesthetics	4.3	Good
Casing Strength	4.5	Very Good

3.10 Quantification of Product Design

Based on the final prototype development results, the following table summarizes the quantified design parameters:

3.11 Product Positioning Analysis

Table 7. Design Parameters of the Developed Product

Parameter	Value	Description
Dimensions (L × W × H, mm)	130 × 55 × 40	More compact compared to reference products
Total Weight	180 grams	Lightweight and portable
Total Volume	286 cm^3	Efficient for mobility
Power Consumption	2.7 W	Powered by a 2235 mAh battery
Operating Time	±15 minutes per session	Sufficient for routine therapy
Number of Cycles per Charging	3–4 full cycles	Efficient for daily use
Battery Charging Duration	±90 minutes	Fast charging via USB
Aerosol Output	0.3 mL/min (average)	Compliant with inhalation therapy standards
Parameter	Value	Description

The developed product design does not solely compete on pricing or technical specifications but strategically highlights ergonomic aesthetics and user convenience, particularly targeting children and non-expert users in home environments. This strategy creates the potential for new market development through differentiation positioning.

The rationale for focusing on these target segments lies in the device's simplified operational interface. The product integrates a single multifunctional button that controls power on/off and regulates the aerosol output, thereby eliminating the need for complex controls or prior training. Additionally, the device is designed to operate without power cables during use, relying on a high-capacity 2235 mAh lithium-ion battery that ensures extended operation across multiple therapy sessions.

By combining ease of use, portability, and appealing visual design, the developed nebulizer offers a compelling value proposition for consumers who prioritize practicality and aesthetics in daily medical device utilization. This positioning differentiates the product from existing alternatives that often require more technical familiarity and provide less ergonomic consideration.

The scores plotted in the positioning matrix were derived from the respondent evaluation data and benchmarking analysis of existing products.

a. Ergonomic Comfort Scores were obtained by averaging Likert-scale ratings (1–5) provided by 78 respondents who assessed the grip comfort and handling of each product during the evaluation phase.

b. Structural Integrity Scores were estimated based on qualitative assessments by users regarding perceived casing strength and durability, combined with comparative observations from handling benchmark devices (Onemed M102, NB06 Nebulizer, Dr. Isla N6).
c. For the final design, the values were confirmed through direct user testing of the 3D-printed prototype, where respondents rated ergonomic aspects and perceived robustness using the same scale.

These combined datasets ensured that the plotted scores accurately reflect both user perception and benchmark comparisons. Table 7 lists the finalized design parameters, including dimensions, mass, and performance specification values. The positioning matrix used to evaluate and categorize the design alternatives is presented in Figure 13.

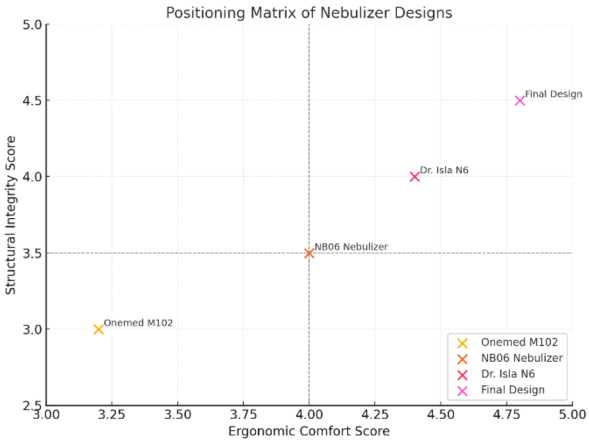

Fig.13. Positioning Matrix Of Nebulizer's Designs

4 Conclusion

This study demonstrates the feasibility of applying user-centered design principles and rapid prototyping techniques to develop a compact, portable mesh nebulizer that addresses common ergonomic and usability limitations observed in existing commercial products. By systematically identifying user needs, translating them into measurable specifications, and evaluating multiple design concepts, the research successfully delivered a prototype with improved grip comfort, reduced weight, and enhanced aesthetic appeal.

Quantitative assessments confirmed that the final design outperformed benchmark devices on key parameters, including ergonomics, casing strength, and ease of use. The integration of a single multifunctional button and a rechargeable lithium-ion battery further contributed to operational simplicity and portability, particularly suitable for children and non-expert users in home environments.

While the prototype fulfilled the targeted design criteria, future work should focus on material optimization for sterilization compliance, extended durability testing, and

certification processes necessary for large-scale production and clinical deployment. Ove rall, the developed product offers a compelling value proposition by combining functionality, user satisfaction, and cost-efficiency, demonstrating the potential to advance home-based respiratory care.

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