NebuFlask: Advancing Usability of Nebulizers to Increase Patient Compliance

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SANTA CLARA UNIVERSITY

Department of Bioengineering

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Murray Bartho, Michael Breshock, Megan Nolte

ENTITLED

NebuFlask: Advancing Usability of Nebulizers to Increase Patient Compliance

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN

BIOENGINEERING

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05/30/2019
NebuFlask: Advancing Usability of Nebulizers to Increase Patient Compliance

By

Murray Bartho, Michael Breshock, Megan Nolte

*Equal participants*

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Bioengineering

of

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Bioengineering

Santa Clara, California

Spring 2019
NebuFlask: Advancing Usability of Nebulizers to Increase Patient Compliance

Murray Bartho, Michael Breshock, Megan Nolte

Department of Bioengineering
Santa Clara University
2019

ABSTRACT

Nebulizers are ubiquitous in the world of medicine. Any patient diagnosed with asthma, pneumonia, cystic fibrosis, chronic obstructive pulmonary disorder (COPD), or any other severe lung disease often use a nebulizer in order to deliver medication to the lungs. Although these technologies are quite common, they are surprisingly outdated. The most commonly used nebulizers today are bulky, loud, awkward to carry around, and must be plugged into an outlet. These aspects of the nebulizer make it a nuisance to use in general and almost impossible to use outside of the home or clinic. The ultrasonic and mesh nebulizers do address most of these issues, however the cost and maintenance required for these types of nebulizers prevent them from being used popularly. By redesigning the jet nebulizer into a water bottle form with a quieter air compressor, we were able to build a prototype that is lighter, quieter, and more discreet than commercially available nebulizers today. This human-centered design empowers users to nebulize in any setting, effectively increasing patient compliance with prescribed medications.
Acknowledgements

There are many people who the NebuFlask team would like to thank for their assistance, advice and input during the yearlong project span.

First and foremost, we would like to thank our advisor, Dr. Prashanth Asuri, of Santa Clara University’s Department of Bioengineering. From connecting the team with the project idea, to making sure the team stayed on track with deliverables and providing sage advice, Dr. Asuri was a critical element of this project from its inception.

Secondly, we would like to thank our two consulting doctorates, Dr. Christopher Kitts from Santa Clara University’s Department of Mechanical Engineering, and Dr. Nikki Saxena, pediatrician from the Pediatric Wellness Group in Redwood City. Dr. Kitts aided us greatly with the prototyping of our design. Dr. Saxena helped to provide the inspiration for this project through her observations in clinic and her friendship with Dr. Asuri.

We would like to thank Yoel Park and Sukruth Krishnakumar, undergraduate engineers from the Department of Mechanical Engineering and the Department of Computer Engineering, respectively. Always eager to learn and help out, these two students also helped with the prototyping process.

Finally, we would like to thank the spaces that have helped us, including the Bioinnovation and Design Lab, the Maker Lab, and the Robotic Systems Lab.
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Chapter 1: Introduction

Nebulizers are a necessary tool in the treatment of lung diseases and disorders. These devices are used to convert liquid medication into an aerosol, or mist, that can be inhaled directly into the patient’s lungs. They can be found in hospitals, clinics, schools and homes and have been around since the 1930s, with their manual predecessors being invented in 1864. Although these devices are staples in the pulmonary world, current models today are surprisingly similar to their 1930s counterparts. Many nebulizer users complain that they are loud, bulky, heavy, unsightly, and must be plugged into the wall, making it extremely difficult to bring with you throughout the day. The NebuFlask aims to address these user complaints by developing a human-centered nebulizer that is discreet, portable, and easy to use.

Our project was initially inspired by a conversation with local pediatrician Dr. Niki Saxena from Pediatric Wellness Group in Redwood City. Dr. Prashanth Asuri, the lead advisor for this project, connected the team with Dr. Saxena as he knew that she had project ideas based on her experience as a pediatrician. The team visited Dr. Saxena’s practice during spring quarter of last year to tour the facilities and have an in depth discussion about potential improvements to be made in the pediatric clinic. There were a few interesting options presented, but by the end of the conversation it was pretty clear which project we wanted to pursue. Dr. Saxena mentioned to the team that nebulizers, a device that delivers drugs to the lungs, were becoming a bit archaic.

Nebulizers are often used to treat asthma. They are an alternative to inhalers, but become necessary to use in the case of severe asthma. Dr. Saxena disclosed to us that she felt the form factor of current nebulizers is impacting her patients’ ability and or willingness to take their medication. She estimated that her patients were taking their medication with a nebulizer about half as often as they should be. She postulated a few reasons why people don’t use their nebulizer as much as they should. The first reason was the session time itself. Most nebulizers today take around 15 minutes or more to fully nebulize a standard dose of medication. This might not sound like a lot of time. However, you must be breathing through the nebulizer mouthpiece for the whole duration of the session. This is especially hard to do with little kids as they have to sit still. Additionally, nebulizers require access to an electrical outlet for power, they
are substantial in weight and they are about the size of a shoebox, making them difficult to use with a busy schedule.

When considering all of these constraints in the nebulization process, on top of the fact that you may need to nebulize six or more times a day, you begin to see why these devices are cumbersome. Dr. Saxena’s suspicions were confirmed when the father of one of her patients complained about the size of nebulizers and asked why there wasn’t a miniaturized version like an e-cig or vaporizer. Through this conversation it became clear that nebulizers are lacking in portability, which limits their usability. Another problem area, especially in children and adolescents, is social stigma. Nebulizers are loud and can be disruptive to use around others. People can feel self-conscious or embarrassed while using these in public.

Nebulizers work by converting a liquid medication into a mist that may be inhaled by the user. This allows the medication to reach the lungs directly. Common medications used in nebulizers include albuterol and ipratropium, and they are most commonly used to treat asthma, cystic fibrosis (CF), chronic obstructive pulmonary disease (COPD), and other respiratory diseases such as pneumonia. These diseases are extremely prevalent, creating a demand for more convenient nebulizers. More than 26 million Americans have asthma, and it is the leading chronic disease in children. More than 65 million people around the world have moderate or severe COPD. There are more than 30,000 people living with cystic fibrosis in the U.S. and more than 70,000 worldwide.

There are three main types of nebulizers on the market today: jet, ultrasonic, and mesh. Jet nebulizers are the most common and work with all common medications used in nebulizers. They require the least maintenance and are the most affordable. The drawbacks of jet nebulizers include inefficient nebulization time, bulkiness, a lack of portability, and noise. Ultrasonic and mesh are quiet, portable, and more efficient in aerosol production. On the other hand, these nebulizers are relatively expensive and high maintenance. In addition, they are not compatible with all medications. For these reasons, we decided to focus on improving the jet nebulizer.
With an end goal of increasing user compliance with nebulizers, we needed to decide exactly where to focus our efforts. We created an online survey to understand what complaints and comments nebulizer users have about their current nebulizers. A screenshot of the survey that includes a couple of the questions can be seen in Figure 1. Dr. Saxena shared the survey with her patients who use nebulizers and the team shared it on their personal social media. One respondent said, “It is really bulky and heavy which makes it difficult to travel with it for long trips. Most times, I just don't bring it with me.” This response highlights the compliance issue as this user will leave their nebulizer behind when traveling. Common themes were complaints about size and noise. These results were extremely informative in deciding where to take our design (see Appendix B).

![Figure 1: User Survey. Image showing perspective of respondent.](image.png)

In our survey we also asked respondents to share their email if they were willing to participate in a more in-depth interview. We asked for more detailed feedback from these respondents as well as our personal connections. These dialogues further confirmed the
portability and social stigma issues involved with nebulizer use. These connections were also invaluable throughout the design process in confirming that we were properly addressing the needs of users.

In addition to needs finding exercises undertaken via surveys and in person interviews, the team also reached out to online communities to understand their needs. The team interacted with the Reddit Cystic Fibrosis and Asthma subreddits over a period of three weeks in October 2018. In addition to posting the Qualtrics survey and receiving responses from the online community, the team was able to read the interactions between members of the community. The impressions left by the interactions in these two subreddits confirmed the team’s focus on portability and social stigma issues associated with nebulizer use.

Two main strategies stood out: reducing treatment time or making frequent treatments more convenient and user friendly. Reducing treatment time would require an increase in the efficiency of the device, so we rejected this goal since industry competition and nebulizer efficacy make this unrealistic for us to accomplish. Instead, we decided to focus on making treatments more user friendly by addressing portability and social stigma, both of which were indicated to be important limiting factors in user surveys and in-person interviews. This led us to our mission statement: increase patient compliance with nebulizer use by improving portability and decreasing social stigma (see Appendix H).

We laid out design criteria for our design in four areas: portability, social stigma, cost, and nebulization time. If we met these criteria, we would be able to significantly improve patient compliance with nebulizers.

Table 1: Design Criteria for NebuFlask

<table>
<thead>
<tr>
<th>Portability</th>
<th>Social Stigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce Weight</td>
<td>Reduce Noise</td>
</tr>
<tr>
<td>Easily Transportable Form</td>
<td>Common, Discreet Form</td>
</tr>
<tr>
<td>Cordless</td>
<td></td>
</tr>
</tbody>
</table>
The Portability improvements would allow the patient to more easily use their nebulizer on the go. By achieving the Social Stigma criteria goals, users would feel comfortable bringing their nebulizer outside the house and using it in public.

Our next aim was to keep the cost at or below the current market price for jet nebulizers. Finally, we wanted to match the industry standard of 15 minute nebulization time (for a standard 3 mL dose of medication) so that patients would not have to sacrifice efficiency for portability.

The size of jet nebulizers is largely due to the compressed air source. We thought if we could make a smaller and quieter source of this compressed air, we could greatly improve the portability and decrease the social stigma of the jet nebulizer.

**Chapter 2: System Level**

2.1 Overview:

A typical jet nebulizer consists of a compressed air source, nebulization cup, and mouthpiece. The compressed air enters the nebulization cup and turns the liquid medication in the reservoir into droplets. The baffle catches the larger droplets that cannot be inhaled by the user. The small, inhalable particles are breathed in by the user through the mouthpiece.
Figure 2: Diagram of nebulization cup.

The NebuFlask design involves automating the compression of a manual nebulizer and packaging it in a water bottle form. An existing nebulization cup was used to ensure acceptable nebulization. To achieve this, we 3D printed a linear actuator to compress the bulb. We designed a scaffold to house the linear actuator, bulb, nebulization cup, Arduino, and batteries inside of our water bottle shell. The bulb is pressed against the ramp on the scaffold by the pusher arm of the linear actuator. Tubing connects the bulb to the nebulization cup. The nebulization cup slides into the scaffolding near the top so that the mouthpiece sticks out of the top of the device. The batteries and Arduino board are glued to shelves on the other side of the scaffold.

2.2 Requirements:

Our mission statement for this project was to increase patient compliance with nebulizer use by improving portability and decreasing social stigma. In order to achieve this, we wanted our nebulizer to be quieter, lighter, discreet, and cordless, all while matching industry standards in nebulization time and price. Our requirements were identified and confirmed through survey results, consultation with a physician, online communities, and in-person interviews.

2.3 Benchmarking Results:
There are many jet nebulizers currently available that all have similar technology. We compared four popular jet nebulizers on the market to create our benchmark. The designs are the Devilbiss PulmoMate Nebulizer System, the Uniclife Portable Compressor System, the Medline Aeromist Compact Nebulizer Compressor and the Compact Vaporizer Compressor. These four jet nebulizers were chosen as they were the most popular on Amazon at the time of purchase.

They vary slightly in size and weight, but all are bulky. In addition, all of these devices needed to be plugged into the wall. All of the jet nebulizers we looked at had motors that made a substantial amount of noise. Current jet nebulizers have a nebulization time of about 15 minutes for a standard 3 mL dose of medication. We decided that increasing this efficiency was out of the scope of our project, but we wanted to at least match this 15 minute standard. We performed a market analysis and found that the average price of the most popular jet nebulizers was about $67.

The noise level of several popular jet nebulizers on the market today was measured. These nebulizers use a simple motor with a piston that compresses the air. These motors make a good amount of noise. They were all around 85 decibels which is comparable to the sound of an automobile. This is pretty disruptive if you are around other people while using your nebulizer.

<table>
<thead>
<tr>
<th>Nebulizer Brand</th>
<th>Noise Level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PulmoMate</td>
<td>86.4</td>
</tr>
<tr>
<td>UnicLife</td>
<td>86.2</td>
</tr>
<tr>
<td>Medline</td>
<td>84.4</td>
</tr>
<tr>
<td>Compressor</td>
<td>83.1</td>
</tr>
</tbody>
</table>
We also measured the weight of these nebulizers. They ranged in weight from 2-5 pounds. The average weight was 3.55 pounds. Although this may not sound like a lot of weight, every pound really adds up when you have to carry it around with you. A pound is especially significant for children who have much smaller frames and less muscle strength.

Table 3: Summary of weight data

<table>
<thead>
<tr>
<th>Nebulizer Brand</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PulmoMate</td>
<td>5.25</td>
</tr>
<tr>
<td>UnicLife</td>
<td>3.28</td>
</tr>
<tr>
<td>Medline</td>
<td>2.72</td>
</tr>
<tr>
<td>Compressor</td>
<td>2.93</td>
</tr>
</tbody>
</table>

2.4 Functional Analysis:

The NebuFlask design has several components. It has a water bottle shaped shell made of PVC pipe and 3D printed PLA. The purpose of this shell is to make the device discreet, reduce noise, and protect the parts inside. Inside the device is an Arduino controlled 3D printed linear actuator. The Arduino Uno is a microcontroller board and controls the speed and direction of the servo motor on the linear actuator. The pusher arm of the linear actuator compresses the bulb creating the compressed air needed to nebulize the medication. The compressed air travels through the tubing and into the nebulization cup. Inside the nebulization cup, the compressed air changes the liquid medication into a mist. We designed a 3D printed scaffold to hold the batteries, Arduino, linear actuator, bulb, and nebulization cup inside of our water bottle form.

2.5 System Level Issues/Decisions:

The team performed several experiments in order to figure out how we would match the output of a standard jet nebulizer with the manual nebulizer. First we measured the volume of air put out by a standard jet nebulizer in 15 seconds. After 15 seconds, the balloon had a circumference of 52.07 centimeters or a volume of about 2.4 liters. We then counted the number
of compressions it took for the DeVilbiss hand-Held Spray nebulizer to generate the same volume of air. It took 95 pumps. In our second experiment we counted the number of hand compressions it took to nebulize 0.5 mL of saline solution. It took 300 pumps. Multiplying that number by six, we arrived at the number of compressions required to nebulize a 3 mL standard dose of medication.

From these experimental results, we calculated that a compression speed of 1.5-2 Hz would be necessary to achieve the 15 minute nebulization time. This is a pretty high frequency for our application and we wanted to come up with a way to lower it. We observed that the existing bulb on the manual nebulizer was quite small and stiff. By replacing the bulb with a larger, softer bulb we could more easily reach our efficiency goals. The existing bulb on the DeVilbiss Hand-Pump nebulizer has a circumference of 41.5 cm. A blood pressure cuff bulb has a circumference of 53 cm. The blood pressure cuff bulb was also less stiff. Since our nebulizer relies on a linear actuator to compress a bulb to provide the compressed air needed to nebulize the medication, the ability for the bulb to deliver this compressed air is paramount. A small, stiff bulb is more difficult for the linear actuator to compress, and provides less volume per compression. Therefore, the larger and less stiff blood pressure cuff bulb could deliver greater airflow per compression, while reducing the mechanical force needed to induce compression, making it a better candidate for our prototype. After performing the same experiments with a blood pressure cuff bulb, we found that we could reduce our frequency to 1 Hz and still achieve 15 minute nebulization.

2.6 Team & Project Management:

One of the main problems encountered in team and project management was how to manage the workflow and distribute the work evenly among team members. A more detailed description can be found in section 2.6.1.

2.6.1 Project Challenges and Constraints

The team encountered several challenges and constraints throughout the process of the creation of the project. One of the initial challenges faced by the team was the challenge of how
to distribute work evenly. We had received feedback from our advisor and from previous teams that the delegation and sharing of work is a crucial part of the project. Our team considered several systems of work delegation and management. At first, we considered more formal forms of project management, like a spreadsheet or Gantt chart, to track our progress. These more formal solutions were rejected for several reasons. First of all, the upkeep required to maintain an organized task-master sheet would be prohibitive. The team received feedback from previous teams that felt that too formal of an organized system required too much upkeep. Upon further consideration, the team decided that an informal approach would be undertaken, with most project tasks being shared equally. The team communicated and delegated mostly through a common group message linked to team member’s phones. Work was divided equally and delegated among team members in the aforementioned message chat. This method provided convenient and successful throughout the completion of the project.

Another major project constraint encountered by the team was the volume of the prototype. The idea behind the project is to redesign the nebulizer into a water-bottle sized vessel, so volume was a high priority when considering how we were going to build the device. At the outset of the project, the team tried to mimic the design of a 21 oz or 32 oz double-walled vacuum sealed water bottle. Upon initial prototyping of the design, and fitting the components together, the team realized that for the initial prototype, more space was required. To solve the challenge of fitting the parts within a water bottle like design, the team used a PVC pipe to accommodate the prototype. The PVC pipe had a little bit of extra space, which allowed for easy removal of the side walls to make changes to the interior prototype. To ensure that the PVC pipe still looked like a traditional double-walled vacuum sealed water bottle, a 3D printed dome was added to the top of the PVC pipe. This mimicked the visual appearance of the water bottles the design was based on, while giving enough interior space for the team to work with.

A third major challenge encountered by the team was finding a bulb with a high enough airflow output to ensure adequate nebulization. Initially, the team found a manual nebulizer pump online and purchased it. The team found that it would require about 1.5-2 Hertz rate of compression of the manual bulb to match the flow output of a standard jet nebulizer. The team determined this was too fast of a rate for the linear actuator, so an alternative solution was found.
The team acquired a sphygmometer cuff bulb and began testing the volume rate output. The team found that with the sphygmometer cuff bulb, a compression rate of roughly 1 Hertz was adequate to provide a flow rate that matched the jet nebulizers. The team ended up designing the linear actuator to match this roughly 1 Hertz flow rate.

2.6.2 Budget

Refer to Appendix H to see the full budget. The team was not constrained by the budget. Part of the leniency with regards to the budget evolved from the team’s focus on rapid prototyping. The rapid prototyping lent itself to cheaper materials, mostly 3D printed PLA plastic materials.

For purchasing purposes, the group again had no issues dividing up purchases between group members. There was an informal agreement between group members regarding who would purchase equipment, and a general rotation was established. All group members reimbursed their purchases via submitting receipts to Matt Blanco in the BIOE office.

2.6.3 Timeline

Seen below in table 3, a general timeline for our project is mentioned, outlining large goals and deliverables.

Table 4: General Timeline of Goals for NebuFlask project.

<table>
<thead>
<tr>
<th></th>
<th>Formation of the team and advisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring Quarter 2018</td>
<td>Visit with Dr. Saxena and discuss potential projects</td>
</tr>
<tr>
<td></td>
<td>Determine project focus</td>
</tr>
<tr>
<td>Summer 2018</td>
<td>Perform reading on needs finding exercises</td>
</tr>
<tr>
<td></td>
<td>Form general timeline for 2018-2019 school year</td>
</tr>
<tr>
<td></td>
<td>Discuss survey design and possibilities</td>
</tr>
<tr>
<td>Quarter</td>
<td>Task</td>
</tr>
<tr>
<td>------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Fall Quarter 2018</td>
<td>Distribute survey to social network and patient population</td>
</tr>
<tr>
<td></td>
<td>Collect survey results and analyze data</td>
</tr>
<tr>
<td></td>
<td>Generate actionable improvements for design</td>
</tr>
<tr>
<td>Winter Quarter 2019</td>
<td>Begin prototyping NebuFlask</td>
</tr>
<tr>
<td></td>
<td>Begin Thesis writing</td>
</tr>
<tr>
<td></td>
<td>Connect with Dr. Kitts regarding mechatronics of NebuFlask</td>
</tr>
<tr>
<td>Spring Quarter 2019</td>
<td>Final prototyping and design</td>
</tr>
<tr>
<td></td>
<td>Final Thesis writing and editing</td>
</tr>
<tr>
<td></td>
<td>Finalize conference slides and present at Senior Design Conference</td>
</tr>
</tbody>
</table>

2.6.4 Design process

Dr. Saxena’s input during the formation of the project and the goals to focus on portability and social stigma were the initial driving forces for the design process. The NebuFlask team took this input and translated it into several design outputs for our prototype. Current jet nebulizers look too much like a “medical device,” and can be embarrassing for patient populations. To attack both issues, we wanted a design that would be discreet to use, both in terms of noise and form function, and portable.

The second moment of inspiration was noticing how prevalent double-walled vacuum sealed water bottles are. They are ubiquitous in school, the workplace, on hikes, and in transit. For these reasons, the team decided to base its prototype around the form function of the aforementioned water bottle.

Once the initial constraints were defined, the team set out to fit the linear actuator and bulb within the shape defined by the water bottle inspiration. Once the general size dimensions
were defined by PVC pipe bought to replicate the internal volume and shape of a water bottle, rapid prototyping processes began to fit the bulb and actuator up inside in a way that would deliver adequate compressions. 3D printing systems with PLA plastic were used to create a scaffolding that could house the required components inside the housing. Many minor modifications of the 3D printed parts were undertaken to maximize the quality of the compression of the bulb, to maximize the air flow output. By the time of the design conference, the scaffolding design was consistently delivering adequate compressions to the bulb.

2.6.5 Risks and mitigations
The main risks involved in this project were due to safety when using various tools. All team members went through Maker Lab supervisor training to ensure proper use of the space and its tools. More on this in chapter 6.4, Health & Safety Considerations. It was also important to keep in mind the practicality of this as a medical device. The team relied on Dr. Saxena to answer medical questions and concerns.

2.6.6 Team management
The team management strategy employed throughout the duration of the design project remained informal, yet effective. A text message group with all members of the team served as the main way to organize and manage tasks and deliverables within the team. Further details on specifics regarding the team management strategy can be found in 2.6.1 Project Challenges and Constraints.
Chapter 3: Subsystems

3.1 Introduction of Roles/Requirements:

The NebuFlask consists of three key subsystems components. These subsystems are the automatic compression system, the nebulization cup/bulb system, and the water bottle housing and scaffolding.

Figure 3: Subsystem design overview. Proposed Automatic compression system (left), Manual Hand-Pump Nebulizer (middle), water bottle housing (right).

3.2 Automatic Compression System:
The automatic compression system is the component that is used to automatically compress the squeeze bulb in order to produce the compressed air necessary for nebulization. We originally thought we would use some sort of robotic claw, as seen on the left in figure 2. However, we thought we would be able to achieve the same results with a much simpler design by using a linear actuator to compress the bulb against a solid surface (see Appendix D). We 3D printed CAD designs of a motor bracket, pin gear, and pusher arm to construct our linear actuator. See below for an image of our final linear actuator prototype and a diagram of a circuit used to power it. To view the 3D CAD designs and Arduino code, see Appendix E and F, respectively.

Figure 4: Linear actuator used as the automatic compressor (left).
Figure 5: Diagram of circuit used to power linear actuator (right).
3.3 Nebulization Cup/Bulb System:

There are many different versions of jet nebulizers on the market today. However, one unchanging constant in these designs is the nebulizer cup. Each may vary slightly in appearance, but the inner workings are mostly the same. The nebulization cup contains the conjunction of the mouthpiece, liquid medication reservoir, baffle, and compressed air source (see Appendix G). The compressed air shoots through the liquid reservoir. The force of this air creates a fountain of the liquid medication, effectively creating an aerosol of medication particles. The baffle separates these small and large particles, allowing only the small ones to flow through, as small particles are the most effective in delivering drugs to the lungs. In order to achieve nebulization, we took a nebulization cup from a PulmoMate nebulizer on the market today. We connected the cup to a bulb from blood pressure cuffs. In this way, every compression of the blood pressure cuff bulb forces compressed air through the nebulizer cup and liquid medication, effectively nebulizing the medication.

![Nebulizer cup](image)

*Figure 6: Nebulizer cup seen in clear at the top. Blood pressure cuff bulb seen in black at the bottom. Black tubing used to connect the two.*

3.4 Water Bottle Housing and Scaffold
To achieve discretion and portability, we created a water bottle housing for the nebulizer. We constructed our water bottle housing using PVC pipe that we cut to a reasonable height. We then 3D printed a curved top with an opening to improve the water bottle appearance while still allowing for the mouthpiece to stick out of the top. Finally, we used adhesive to bond the pipe and top together and spray painted everything black. We also added stickers to further simulate the water bottle design.

Figure 7: CAD design of curved top (left), PVC pipe (middle), NebuFlask exterior (right).
Chapter 4: System Integrations and Testing

4.1 NebuFlask Scaffold Integration

One of the main challenges encountered in this project was figuring out how to integrate all of the subsystems together. The team decided the best way to do so was to design a skeleton/scaffold that the nebulizer components could be attached to. Using SolidWorks, the team constructed a 3D design consisting of a circular base supporting a tall, rectangular, bookshelf-like post. The front side of the scaffold holds shelves for the nebulizer cup, linear actuator, and a ramp at the base to hold the squeeze bulb in place. The back side of the scaffold holds shelves and space for the batteries, wires, and circuit that powers the device (see figure 6).

![3D CAD of scaffold. Isometric view of front (left). Isometric view of back (right). Subsystems integrated on 3D-printed scaffold (middle).]

4.2 Weight Evaluation

In order to properly evaluate the improvements made to usability, the NebuFlask prototype was compared to the four most popular jet nebulizers commercially available today. The NebuFlask prototype weighs 2.16 pounds. This is more than a pound less than the 3.55 pound average we found when looking at current jet nebulizers. It is more than a half a pound lighter than even the lightest jet nebulizer sampled (see figure 7). To put this into perspective,
2.16 pounds weighs less than a full liter water bottle (2.2 lbs). This makes it a reasonable weight to be transported.

![Weights of Various Jet Nebulizers](image)

*Figure 9: Graph of weights of various commercially available jet nebulizers and NebuFlask prototype.*

4.3 Noise Evaluation
The NebuFlask design is significantly quieter than the standard jet nebulizer. The market jet nebulizers averaged around 85 decibels, about the same amount of noise that a car makes. The NebuFlask makes about 65 decibels of noise, somewhere between the noise of a quiet street and normal conversation (see figure 8). This level of noise is much less disruptive than standard jet nebulizers. Many nebulizer users that the team spoke with complained of their nebulizer being too loud. Reducing the amount of noise that the nebulizer makes greatly reduced the embarrassment and hesitation around using it in public.

![Sound Reduction](image)

**Figure 10:** Plot of avg noise, measured in decibels, of various jet nebulizers (warm colors) and NebuFlask (blue) (left). Noise and decibel reference chart (right).

### 4.4 Efficiency

After measuring the design criteria related to social stigma and portability, the team moved on to analyze the nebulization efficiency of the device. Upon activation of the device, the nebulization process was initiated, and vapors began to gather in the nebulization cup. However, the creation of the vapor was less consistent than industry nebulizers. The reliability and efficiency of the NebuFlask will be one of the main focuses of the future work on the project (see section 7.2).
Chapter 5: Cost, Pricing and Reimbursement

5.1 Prototype Cost:

Seen below in Table 4, the overall cost of the NebuFlask was roughly $46.00. All prices listed are the cost of buying the item from retail sources. Significant price reduction could be achieved for many parts by buying wholesale from the manufacturer.

The cost of the NebuFlask makes it equal to or cheaper than most jet nebulizers on the market, including the four purchased for competition testing by the team.

Table 5: Itemized cost breakdown of prototype

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<tr>
<th>Subsystem</th>
<th>Part</th>
<th>Cost</th>
</tr>
</thead>
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<tr>
<td>Water Bottle Housing</td>
<td>PVC Pipe</td>
<td>$3.00</td>
</tr>
<tr>
<td></td>
<td>3D Printed Parts</td>
<td>$4.00</td>
</tr>
<tr>
<td>Automatic Compressor</td>
<td>Arduino Uno</td>
<td>$16.00</td>
</tr>
<tr>
<td></td>
<td>Servo Motor</td>
<td>$9.00</td>
</tr>
<tr>
<td></td>
<td>3D Printed Parts</td>
<td>$2.00</td>
</tr>
<tr>
<td></td>
<td>Batteries</td>
<td>$4.00</td>
</tr>
<tr>
<td>Nebulizer Component</td>
<td>Blood Pressure Cuff Bulb</td>
<td>$5.00</td>
</tr>
<tr>
<td></td>
<td>Reservoir, Mouthpiece and Tubing</td>
<td>$3.00</td>
</tr>
</tbody>
</table>

Total                          | $46.00
The cost of our prototype would overall decrease in mass production. Based on information found from searching manufacturing costs online, we found we would be able to significantly reduce the overall cost of each subsystem. The water bottle housing could be manufactured at $3, the automatic compressor would be replaced with a linear actuator priced at $18, and the nebulizer components (bulb and cup) would cost a total of $1 all at mass production. This puts our total manufacturing cost at $22 for a market ready product.

5.2 Pricing and Reimbursement

![Portability vs. Cost](image)

*Figure 11:* Graph comparing portability to cost for the three main nebulizer types, the manual handheld nebulizer, and NebuFlask.

Considering current market prices, selling the NebuFlask at $46 would be a reasonable cost to the consumer while bringing in enough profit to be sustainable. As discussed above, the total manufacturing cost for a commercial NebuFlask would be about $22. If we sell the NebuFlask at $46 we would make a profit of $44 per device sold. We expect that this profit would make the NebuFlask a commercially viable product.
We believe the NebuFlask should be available for insurance reimbursement, likely, covered under HCPCS code E0570 as most jet nebulizers are. We expect that we would be covered because we’ve been able to reduce the price from standard jet nebulizers while significantly improving the portability and overall usability of the product. Additionally, the NebuFlask has elevated the jet nebulizer to nearly the same portability as modern ultrasonic and mesh nebulizers while remaining at less than half the cost. Consumers without access to health insurance should also be satisfied that the price of the NebuFlask is about the price of the cheapest jet nebulizers, while providing state-of-the-art human-centered design usability.
Chapter 6: Engineering Standards/Realistic Constraints

6.1 Ethical Considerations

Ethical considerations were at the forefront of the team’s mind since the beginning of the Senior Design project. One of the most important ethical considerations in the medical device field is that of pricing. The United States is one of the few industrialized countries that does not regulate medical device pricing. This has led to an unregulated field wherein expensive medical devices run rampant. Medical debt is the most common kind of debt in the United States, and expensive medical devices no doubt contribute to this phenomenon. About 16% of American families in 2017 had difficulty paying their medical debts. Considering all this, the NebuFlask team decided that one of the main ethical concerns going into the project was to keep the cost of the NebuFlask at or below comparable alternatives, as well as pricing the NebuFlask for all Americans. More pricing specifics can be found in section 6.4.

6.2 Scientific Considerations

One of the initial scientific considerations worked through at the outset of the project was the possibility of vaporization technology being used to miniaturize the nebulizer. The initial impetus for the project had come from a patient’s father inquiring why there was not a nebulizer that was the size of an e-cigarette, since both produced vapor. Disregarding other ethical concerns about designing a medical nebulizer to mimic e-cigarettes, the team received crucial medical science feedback in this regard. Most e-cigarette designs are vaporisers that use a heating element to turn a liquid or gel medication into a vapor. The team received feedback from Dr. Saxena that many medications can be destroyed or rendered inactive when exposed to a heating element. Nebulizers use a source of compressed gas to turn the liquid medication into an aerosol, and therefore avoid this issue. While medications are able to retain their chemical integrity when at the physiological temperature of 98.6 degrees Fahrenheit, heating elements used in e-cigarette designs surpass this temperature and can inactivate the drug chemical.

6.3 Economic Considerations
As mentioned in section 6.1, the price of medical devices, as well as healthcare in general, has become cost-prohibitive for many Americans. It is important for the NebuFlask to be affordable for all Americans and cost-comparable with its peer medical devices. As seen in table 4 (section 5.1), the NebuFlask costs around $46 to produce.

Comparable compressed air nebulizers cost around $40-80, putting our prototype solidly at the lower end of this range. Additionally, we believe that our prototype offers the best compromise between portability and affordability on the market. In figure 9 (section 5.2), we compare portability to cost with the NebuFlask, compressed air nebulizers, and other types of nebulizers. To calculate cost, we averaged 2-5 of the top selling nebulizers in each category. To calculate portability, the NebuFlask team used a gestalt assessment of the overall portability of the device, assigning a score between 1 and 10, with 10 being the most portable. Factors such as size, weight, convenience and form factor went in to determining the overall portability score.

As can be seen in figure 9 ultrasonic and mesh nebulizers have better portability than the NebuFlask, but most range from $100 to $250. Also, compressed air nebulizers tend to be between $40 and $90, but are limited by their bulky size. The NebuFlask provides good value for money as an affordable and portable option.

6.4 Health & Safety Considerations

Above all, we made sure that health and safety considerations were a prominent focus of the project. Two main groups emerged as essential in this regard. One was the NebuFlask team itself, including its array of advisors and student assistants. The second group was those who would use the device, both in testing and once the product may find its way onto the market.

First, ensuring the safety of the NebuFlask team during prototyping, testing, enacting design changes, etc. was always a serious matter. First, the NebuFlask team was Supervisor trained in the Maker Lab to make sure that they were proficient in all safety protocols, as well as adequately familiar with the tools in the lab they would be using. While in the Maker Lab, the team always wore long pants, close-toed shoes, and safety glasses as per Maker Lab protocol. After being supervisor trained, any prototyping or design activity that involved electrical work,
liquids, sharp-edged or otherwise dangerous tools besides scissors was conducted in the Maker Lab with at least 2 people present. Having one other person in the Maker Lab during use is Lab policy, and the NebuFlask team ensured compliance in this regard, as having multiple people greatly reduces risk of injury or emergency. Most other low-risk activities, such as using super-glue or scissors, was still done in the presence of two people for safety purposes. The NebuFlask team also communicated general safety guidelines to the two student assistants to ensure they also were safety compliant in their research.

Another step the team took to ensure the safety of those working on the NebuFlask, as well as compliance with federal FDA regulations, was to never, under any circumstances, load the nebulization chamber with medication. The NebuFlask loaded with medication becomes a medical device, and therefore must be compliant to a litany of FDA regulations. To even get a medical device in use by a patient, numerous paperwork heavy steps and design controls must be initiated by those behind the medical device. The NebuFlask team did not have FDA permission to do any kind of medical trials, and therefore ensured medication never entered the cup of the prototype. To see if the prototype was nebulizing effectively, 0.9% saline or water was inserted into the cup, but never medication.

In addition to securing the safety of the NebuFlask team during the production, prototyping and testing of the design, the safety of the end user was always in mind. To this end, the NebuFlask was designed to minimize injury in multiple ways. One such was was the elimination of pinch points, sharp corners, and rough surfaces on the outside of the nebulizer. Since the exterior material is either smooth PVC or PLA plastic, the risk of injury from contact with the bottle is minimal. The rounded top of the NebuFlask mimics real-life water bottles, but also serves a safety purpose as well, in that its rounded edges also reduce the risk of blunt or sharp force trauma. The reduced weight of the NebuFlask in comparison to other nebulizers also makes it so dropping the NebuFlask carries less force. This would reduce the impact force if the NebuFlask gets dropped on surfaces or another person.

6.5 Manufacturability Considerations
There are numerous manufacturability considerations that were looked at during the development of this project. One consideration that was brought up during the project was the minimization of the device. The minimization of the interior volume taken up by the prototype linear actuator could be drastic if the right manufacturing decisions were made. One such minimization involves replacing the Arduino and circuitry with a printed circuit board or PCB. PCBs can be made very cheaply for a simple electronic circuit seen in the NebuFlask. The team looked at Fritzing.com and found that it was possible to replace the Arduino and the breadboard with a printed circuit board. For manufacturing, replacing the Arduino with a printed circuit board could save a large amount of space.

6.6 Usability Considerations

Usability considerations are an integral part of the design process when it comes to the NebuFlask. If the NebuFlask team set out to do just one thing, it would be to increase the usability of nebulizers. Part of our emphasis on this stems from our survey we sent out, which made it clear that convenience and usability of nebulizers were a limiting factor to their use. As can be seen in table 5 below, over half the respondents had an issue with their nebulizer that prevents them from using their nebulizer. Convenience and time are both very closely tied to usability. If something isn’t convenient, it isn’t usable, likewise for something that takes too much time.
Table 6: Selected Survey Responses

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<thead>
<tr>
<th>Element that Prevents Nebulizer Use</th>
<th>Number of Respondents</th>
</tr>
</thead>
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<td>Convenience</td>
<td>5</td>
</tr>
<tr>
<td>Time</td>
<td>2</td>
</tr>
<tr>
<td>Nothing</td>
<td>6</td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
</tr>
</tbody>
</table>
Chapter 7: Conclusion

7.1 Summary:

The nebulizers on the market today don’t adequately address the needs of the user. The mesh and ultrasonic nebulizers that are portable and efficient have drawbacks that keep them from being the most popular type of nebulizer. Ultrasonic and mesh nebulizers are expensive, hard to maintain, and cannot be used with all nebulizer medications. Jet nebulizers are the most widely used nebulizers. They are relatively inexpensive, easy to maintain, and are compatible with all medications. Where jet nebulizers fall short is in terms of portability and efficiency. Most jet nebulizers are bulky, loud, and need to be plugged into an outlet. It takes about fifteen minutes to nebulize a medication using a jet nebulizer which is a long time to be tied to a wall. In addition, the noise and size can make patients embarrassed to use their nebulizer in front of others. For all these reasons, nebulizer user compliance is very low—around 50% of prescribed use. Our team’s goal was to increase nebulizer user compliance by improving portability and decreasing social stigma.

The team spent a lot of time conducting needs-finding activities in order to identify the features to focus on. Through discussions with Dr. Saxena, it was confirmed that social stigma is a serious concern in terms of compliance, especially with children and young adults. Through surveys put out on social media and in-person interviews, portability was identified as a common complaint and barrier to use. The team decided to focus on reducing the weight and noise of the device, eliminate the need to be plugged into a wall, and creating a discreet form. The team wanted to achieve this while also matching industry standard nebulization time and price.

The prototype successfully met almost all of the design criteria. It is lighter and quieter than the average jet nebulizer on the market. The NebuFlask is cordless and is packaged in a common form, a water bottle. The device can fit in a backpack water bottle holder (see Appendix J). The cost is comparable to current jet nebulizers on the market. The efficiency is still a work in progress as it does not currently stack up to the industry standard. Additionally the team received lots of positive feedback from nebulizer users about the concept of the design.
7.2 Future Work:

Our prototype was successful in meeting many of our goals, but there is still room for improvement. Although we successfully reduced the weight as compared to standard jet nebulizers, the size of our prototype is larger than a standard 32 oz. Hydro Flask (the size we were aiming to meet). This makes our prototype slightly less discreet and convenient to carry around. There are several easy ways to reduce size. The linear actuator is currently controlled by a Arduino Uno board, which measures 69 x 53 mm. The only part of the board that is needed is the microcontroller, which measures 37 x 7 mm. This can be removed from the Arduino, or an even smaller microcontroller could be used. Additionally, the prototype has four AA batteries and a 9V battery currently powering the device. A smaller, rechargeable lithium battery could replace these five rather large batteries.

Another area that could use improvement is efficiency. The prototype does not currently match the efficiency goal of 15 minutes to nebulize 3 mL of medication. To address this, the team is testing with parallel processing. By using two blood pressure cuff bulbs, we can double the output of air and increase efficiency of our device. In addition, if the bulbs are compressed alternately, there can be a steady stream of mist for the user to inhale.

Figure 12: Parallel processing of the air compressing bulbs with two linear actuators working in tandem (left). Y-connector used to combine outputs of both bulbs into one cup (right).
In order to make our design more robust and even quieter, future designs would incorporate a metal shell instead of the current PVC and PLA one. A metal shell would help protect the parts inside from drops and other damage. In addition, a metal shell would better insulate the device, subduing the noise even more.

A final area the team wants to look into further is establishing intellectual property rights for our design. Several industry professionals have recommended to the team to apply for a design patent.

**Bibliography**


“Asthma Facts.” *Asthma and Allergy Foundation of America*, www.aafa.org/asthma-facts/.


Medical Device Price Differentials In The U.S. And Europe – Rethinking Price Regulation?, Health Affairs Blog, December 7, 2018. DOI: 10.1377/hblog20181206.716970

“Nebulizer with Compression.” Healthcare Common Procedure Coding System, hcpcs.codes/e-codes/E0570/.


Appendix

Appendix A: Vaporizing Efficiency/Reservoir Volume Experiment

Experimental Set-Up:

Materials:
- 3 compressor nebulizers
- Saline solution
- Syringes (no needles)
- Plastic bag to collect vapor
- Bowl
- Compressed air canister
- Ring Stand + Clamp

Procedure:
For nebulizer tests,
1. Load the reservoir of one of the nebulizers with 3 ml of saline.
2. Cover the mouthpiece with a plastic bag to collect the vapor.
3. Run the nebulizer for 15 minutes, collecting the vapor in a plastic bag.
4. Turn the nebulizer off and measure the amount of liquid remaining in the reservoir using the syringe.
5. Pour out remaining liquid into sink. Wash and dry reservoir sufficiently.
6. Repeat with the other two nebulizers.

For testing with compressed air,
1. Hook up the compressed air canister to the nebulizer tubing. Fill the reservoir with 3 ml of saline.
2. Cover the mouthpiece with a plastic bag to collect the vapor.
3. Let the air flow through the tubing for about 30 seconds.
4. Measure the amount of solution remaining in the reservoir.
5. Pour out remaining liquid into sink. Wash and dry reservoir sufficiently.

Clean up:
- Pour out any remaining liquid in reservoir, syringe, vapor collecting bag, or bowl.
- Sufficiently clean and dry reservoir and syringes
- Wipe down desk with wet paper towel and dry
- Return any equipment borrowed (compressed air canister, ring stand)
- Put away nebulizers and mouthpieces
- Throw away vapor collecting bag unless it can be reused

Appendix B: Market Analysis
<table>
<thead>
<tr>
<th>Name</th>
<th>Link</th>
<th>Type</th>
<th>Cost</th>
<th>Portable</th>
<th>User Reviews (/5)</th>
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<td>PARI Vios</td>
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<td>Compressed Air</td>
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<td>Yes</td>
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<td>(3 reviews)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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Q1 - What brand of nebulizer do you use?

- Pari trek s
- Pari Vios Pro
- Pulmo Aide by DeVillbiss
- Kerae Medical
- pari
- Not Sure
- not sure
- tbh not sure. whatever cowell provided
- Vios
- Pulmomate
- no clue

Q2 - How satisfied are you with your nebulizer?
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<tr>
<th>#</th>
<th>Field</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std Deviation</th>
<th>Variance</th>
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<td>1</td>
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<td>Slightly satisfied</td>
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<td>4</td>
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<td>Slightly dissatisfied</td>
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| Total                                    | 100%   | 11    |

Q3 - How easy is it for you to use your nebulizer?
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Q4 - How important is it for you to have a mobile nebulizer?

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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>4</td>
<td>Slightly important</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>5</td>
<td>Not at all important</td>
<td>18.18%</td>
<td>2</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Total</td>
<td>100%</td>
<td>11</td>
<td></td>
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</tbody>
</table>

Q5 - How often do you use your nebulizer?

<table>
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<tr>
<th></th>
<th>Field</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std Deviation</th>
<th>Variance</th>
<th>Count</th>
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<tr>
<td>1</td>
<td>How often do you use your nebulizer? - Selected Choice</td>
<td>1.00</td>
<td>4.00</td>
<td>2.50</td>
<td>1.38</td>
<td>1.92</td>
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<tr>
<td>#</td>
<td>Frequency</td>
<td>Percentage</td>
<td>Count</td>
<td></td>
<td></td>
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<tr>
<td>---</td>
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<td>------------</td>
<td>-------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Daily</td>
<td>41.67%</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Weekly</td>
<td>8.33%</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Monthly</td>
<td>8.33%</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Only When Needed</td>
<td>41.67%</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Other</td>
<td>0.00%</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>100%</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

**Q6 - What prevents you from using a nebulizer?**

<table>
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<tr>
<th>#</th>
<th>Answer</th>
<th>%</th>
<th>Count</th>
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</thead>
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<td>1</td>
<td>Time</td>
<td>25.00%</td>
<td>4</td>
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<td>2</td>
<td>Convenience</td>
<td>37.50%</td>
<td>6</td>
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<td>3</td>
<td>Cost</td>
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<td>0</td>
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<td>4</td>
<td>Nothing prevents me from using a nebulizer</td>
<td>31.25%</td>
<td>5</td>
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<tr>
<td>5</td>
<td>Other</td>
<td>6.25%</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>100%</td>
<td>16</td>
</tr>
</tbody>
</table>
Energy - a lot of the time I get home from a long day and just want to go to bed! setting up the nebulizer and spending time hooked up can be exhausting

Q7 - If you could change one thing about your nebulizer what would it be?

If you could change one thing about your nebulizer what would it be?

Battery life and cord

Being able to move around while doing it! Would love to be able to do laundry, cook dinner, do other things around the house while not being hooked up to the wall would be awesome. Also it is really bulky and heavy which makes it difficult to travel with it for long trips. Most times, I just don't bring it with me.

Size— compressor is very big.

Love that it's a reliable workhorse, wish it was quieter and faster. It's like the saying, you want it to be fast, cheap, reliable and quiet, but you can only pick two.

Easier access with few steps to get the nebulizer working.

i will email all my complaints, ive used 4 different nebulizers

I wish that it would either be more mobile or nebulize my medication quicker

cost
something to do with the saliva.... it's weird to swallow cold saliva and gross to let it drop everywhere

doesn’t need to be plugged into wall, make it chargeable

The meds condense along the side of the cup and it needs to be knocked/wiggled to get the drops down to the bottom of the cup

The discomfort of the strap and the harsh plastic. The shape didn't fit well on my face. Additionally, it had a bad plastic smell.

Appendix D: Initial NebuFlask Prototype Design Sketches
Appendix E: 3D CAD Designs

Linear Actuator Parts
Gear:

Pusher Arm:

Motor Bracket:

NebuFlask Prototype
Curved Bottle Top:
Appendix F: Arduino Code

Single Processing:
```cpp
#include <Servo.h>
Servo servo1;

void setup()
{
    servo1.attach(7); /* setting which pin servo
                        is attached to on board */
}

void loop() /* continuous loop until turned off */
{
    servo1.write(75); /* setting speed in forward direction */
    delay(1000); /* pause between switching directions */
    servo1.write(105); /* setting same speed in reverse direction */
    delay(1000); /* pause */
}

Parallel Processing:

#include <Servo.h>
Servo servo1;
```
Servo servo2;
void setup()
{
    servol.attach(8); /* setting which pin servo 
is attached to on board */
    servo2.attach(6);
}
void loop() /* continuous loop until turned off */
{
    servol.write(76); /* setting speed in forward direction */
    servo2.write(76);
    delay(1000); /* pause between switching directions */
    servol.write(105); /* setting same speed in reverse direction */
    servo2.write(105);
    delay(1000); /* pause */
}
Appendix G: Budget Proposal

Engineering Undergraduate Programs Senior Design Funding Proposal

Budget

Team: Murray Bartho, Michael Breshock, Megan Nolte

Advisor: Prashanth Asuri, PhD, MBA

10/19/18

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost:</th>
<th>Funding Allocation:</th>
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<tbody>
<tr>
<td>Ultrasonic Nebulizer</td>
<td>$150.00</td>
<td>Undergraduate Programs</td>
</tr>
<tr>
<td>Mesh Nebulizer</td>
<td>$200.00</td>
<td>Undergraduate Programs</td>
</tr>
<tr>
<td>Miscellaneous Parts/Equipment</td>
<td>$583.00</td>
<td>Undergraduate Programs</td>
</tr>
<tr>
<td>3D Print Material</td>
<td>$50.00</td>
<td>Undergraduate Programs</td>
</tr>
<tr>
<td>Lab Equipment (glassware, etc)</td>
<td>$250.00</td>
<td>Undergraduate Programs</td>
</tr>
<tr>
<td>Prototype Components</td>
<td>$283.00</td>
<td>Undergraduate Programs</td>
</tr>
<tr>
<td>Drug solutions</td>
<td>$500.00</td>
<td>Undergraduate Programs</td>
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<tr>
<td>Saline</td>
<td>$20.00</td>
<td>Undergraduate Programs</td>
</tr>
<tr>
<td>Arduino Uno Rev3</td>
<td>$22.00</td>
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<tr>
<td>Arduino Actuator</td>
<td>$25.00</td>
<td>Undergraduate Programs</td>
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Total Funding Acquired $1,500.00

Equipment Secured:

Uniclife Portable Compressor System Kit $35.60

NEARTOP Air Compressor Personal $31.99

Compact Vaporizer Compressor $29.89

DeVilbiss 45 Lexan Plastic Pocket Nebulizer $34.99

Total Cost of Equipment Acquired: $132.47

Appendix H: Decision Tree

Increase user compliance of nebulizers

Reduce treatment time

Make frequent treatments convenient, user friendly

Increase efficiency

Portability

Social Stigma

Rejected. Industry competition and nebulizer efficacy make this an unrealistic goal.

Accepted. User surveys indicate portability as an important limiting factor.

Accepted. Feedback from Dr. Saxena describes social stigma as an important limiting factor.
Appendix I: Electrical Schematic

Appendix J: Patient Empathy Testing
Appendix K: Medical FAQ

Question 1: Can we spread out the dosage over an hour in smaller nebulization sessions?  
Answer: Not possible due to decreased compliance, not as convenient, minimized efficacy.

Question 2: More concentrated liquid medication to shorten nebulization time?  
Answer: Not feasible as 3 ml is the industry standard dose.