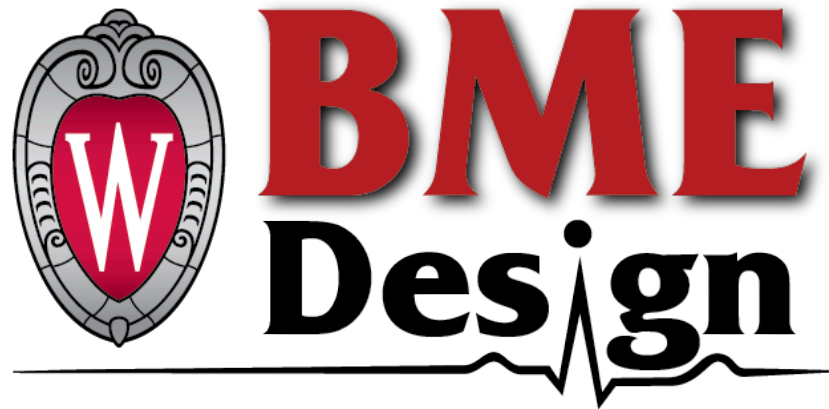




Flow Limitation During Forced Expiration in an Airway Model - BME 200/300

Preliminary Report

October 7, 2026

Section 304

Client:	Dr. Mehmet Orman	maorman@wisc.edu
Advisor:	Dr. Chris Green, MD	cggreen@wisc.edu
Team:	Lakshika Nanda Kumar Reddy (Co-Leader)	nandakumarre@wisc.edu
	Julia Shefchik (Co-Leader)	jshefchik2@wisc.edu
	Caroline Blust (Communicator)	cblust@wisc.edu
	Eliza Kubicek (BSAC)	eckubicek@wisc.edu
	Brady Mayer (BPAG)	bjmayer3@wisc.edu
	Jillian Seibert (BWIG)	jjseibert@wisc.edu

Abstract

Flow limitation occurs when increased expiratory effort no longer increases airflow because the airway itself becomes the limiting factor. It underlies the spirometric findings of obstructive diseases such as asthma and chronic obstructive pulmonary disease (COPD), which together cause millions of deaths annually [1, 2]. The mechanism is conceptually demanding for medical students and fellows, and existing resources do not convey it physically. Computational fluid dynamics and wave-speed models either omit external pressure or exist only *in silico*, and static anatomical models cannot show dynamic compression [3, 4]. This project presents a physical teaching model that demonstrates the equal pressure point and a choke point moving distally during forced expiration. The proposed final design is a $20 \times 20 \times 20$ cm sealed chamber containing a branching airway based on the stochastic model, 3D-printed from Formlabs Elastic 50A, with water balloons representing the alveoli. Compressed air and vacuum lines control the pressure surrounding the airway. Testing comprises pressure characterization of the balloons, finite element analysis in SolidWorks, tensile comparison with the previous year's airway on an MTS machine, and at least ten simulated forced expirations recorded on video and analyzed in ImageJ. A successful trial requires at least a 50% reduction in airway diameter and distal movement of the choke point. These evaluations will determine whether the model reproduces flow limitation reliably enough to support an educational video for teaching spirometry and obstructive airway disease.

Table of Contents

Introduction	4
Preliminary Materials Designs and Evaluation	5
Material Preliminary Designs	5
Airway Preliminary Designs	11
Alveoli Preliminary Designs	16
Proposed Final Design	21
Fabrication	22
Testing and Results	23
Discussion	25
Conclusion	26
References	27
Appendix	27
Appendix A: Product Design Specifications	32
Appendix B: Airway Fabrication Protocol	34
Appendix C: Expense Table	35

Introduction

Chronic obstructive pulmonary disease (COPD) and asthma are major contributors to global respiratory morbidity and mortality. COPD caused an estimated 3.4 million deaths in 2023 and is the third leading cause of death worldwide [5]. Asthma affected approximately 262 million people and caused 455,000 deaths in 2019, predominantly in lower-middle-income countries, where under-diagnosis and under-treatment persist [2]. Spirometry is central to the diagnosis and monitoring of obstructive diseases, and interpreting its flow-volume curves requires an understanding of the airway mechanics that shape them [6]. The deterministic factor is flow limitation, where once the airway is compressed during forced expiration, airflow becomes independent of expiratory effort [1]. Flow limitation can occur in healthy individuals during forced expiration. In obstructive diseases, however, reduced structural support of the airway wall and diminished elastic recoil makes the airways more collapsible, so that the choke point forms at lower flows and lung volumes and becomes pronounced. This is conceptually demanding as it contradicts the intuition that greater effort yields greater flow, and it is difficult to convey with text or static diagrams because the compression varies dynamically along the airway. Existing resources, however, do not convey this mechanism physically. The computational fluid dynamics model developed at Yamaguchi University reconstructs airway geometry from CT data but omits external pressure and therefore cannot represent pressure drops or choke points [3]. The Polak and Yutchen model describes wave-speed flow limitation and choke point formation across the bronchial tree, but only in silico [4]. As a result, learners cannot observe the equal pressure point and choke point develop and migrate distally through a compliant, branching airway. A physical model that reproduces this dynamic compression is therefore needed to support instruction on the mechanics underlying spirometry in obstructive disease.

Background and Required Research

The human respiratory system is a complex system of branching airways through approximately 23 generations, starting at the trachea and ending at the alveoli. Understanding the anatomy of the human airways is essential to properly model these structures.

During forced expiration, the positive pressure inside the chest cavity, known as pleural pressure, compresses the flexible airways inside of the lungs. As airflow moves proximally towards the mouth, frictional resistance from airway walls causes internal pressure to decrease. At the location at which the internal airway pressure falls below the pleural pressure, the equal pressure point, the airway wall compresses. This commonly occurs within the first few generations of the airways. When air velocity reaches the speed of pressure waves moving along the flexible walls, a choke point is formed which prevents further increases in expiration regardless of added effort [7, 8].

The movement of chokepoints is heavily governed by the internal geometry of the bronchial tree. While airways have been before modeled with symmetrical branching across generations, the anatomy of the human lungs is essentially stochastic with asymmetrical branch length, angles, and diameters across early generations which creates localized flow resistance and unequal pressures. Incorporating stochastic branching into airway modeling is therefore critical to showcase chokepoint formation and movement [9].

Alongside geometry, physical tissue properties of the lung airways is important to consider when determining how easily a segment may collapse when under pressure. The bronchial tree is made of a gradient

of different tissues, with more cartilaginous tissue at the trachea, and almost solely more flexible smooth muscle in later generations of the bronchioles [10]. Additionally, late generation of the airways are physically anchored to the elastic alveolar network which creates a grip on the airways to resist collapse. Modeling both the differences in wall compliance and alveoli elasticity are crucial to create a physiologically accurate model of flow limitation during forced expiration.

Client Information

The client for this project is Dr. Green, a retired pulmonologist and current educator to medical students. In order to more effectively teach his students, Dr. Green requires a physical aid and educational video to play that can adequately demonstrate airway collapse, chokepoint formation, and the distal movement of chokepoints during forced expiration.

Design Specifications

The physical 3D printed airway must accurately represent human physiology from the main bronchi and through subsequent generations. The model must fit inside of the existing pressure chamber which creates a size restraint of no larger than 15 cm and the wall thickness and dimension will be accurate based on realistic airway ratios between subsequent branches. When the choke points are formed there will be a 50% decrease in lumen size, and it must be able to withstand repeated pressure cycles during testing. Finally, the complete assembly including the production of the airway, balloon elastics, and chamber parts must be fabricated within a budget of under \$1000 and completed before the end of the semester. A full description of the product design specifications can be seen in Appendix A.

Preliminary Materials Designs and Evaluation

Material Preliminary Designs



Figure 1: Formlabs Flexible 80A Resin Depiction [11]

The first material option is FormLabs Flexible 80A, which is a resin filament available for 3D printing on the FormLabs Form 4 printers in the Design Innovation Lab at Wendt. Flexible 80A is a hard flexible resin with a shore hardness of 80A and a relatively high ultimate tensile strength of 8.9 MPa [11]. Flexible 80A is known for its durability in bending, flexing, and compression as one of the stiffest soft/elastic resins available from FormLabs [11]. It is available for print in clear, white, and black.



Figure 2: FormLabs Flexible 50A Resin Depiction [12]

The second material option is FormLabs Flexible 50A Resin, which is a photopolymer elastomer used to 3D print parts that closely mimic the feel and behavior of molded silicon. It is widely used in soft-tissue anatomical models and medical stimulation devices because it prints transparent, allowing visibility into internal features, and can be shaped directly through SLA printing rather than casting. Its greatest strength lies in its high elasticity and rapid springback, with an elongation at break of 160% and a tear strength of 12.3 kN/m that allow it to bend, stretch, and compress through repeated cycles without tearing [12, 13]. However, its relatively low durometer (50A) and a lower ultimate tensile strength of 3.4 MPa, and its tendency to remain slightly tacky unless post-curing and finishing steps are followed carefully limit its use as a rigid structural component [12].

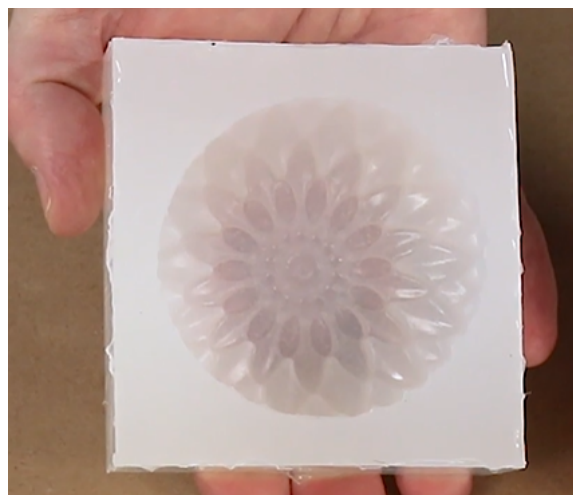
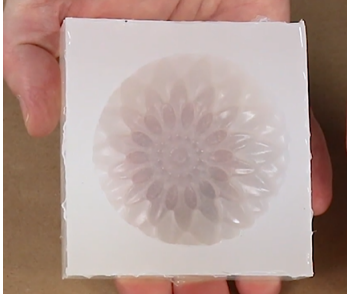


Figure 3: Smooth-On Mold Star 31T Silicone Depiction [14]

The third material option is Smooth-On Mold Star, which is a platinum silicone that is tear-resistant and exhibits very low shrinkage over time. Because of its low viscosity, vacuum degassing of the mold to eliminate trapped air is rarely necessary, and its 1A:1B mix ratio by volume eliminates the need for precise weighing. The Mold Star 31T silicone has a 30A Shore hardness, a tensile strength of 2.9 MPa, and an elongation at break of 400%. The relatively long cure time of 6 hours allows ample time to pour the silicone accurately and makes premature curing less likely [15]. In order to successfully fabricate the airway, a sacrificial mold will be 3D printed using polyvinyl alcohol (PVA), a polymer known for its excellent water-solubility [16]. Mold Star 31T is waterproof and heat resistant, meaning that it will be possible to fully dissolve the PVA material used for the sacrificial mold without harming the airway model.

Table 1: The design matrix for 3D printing material choices

		Design 1: FormLabs Flexible 80A		Design 2: FormLabs Flexible 50A		Design 3: Smooth-On Mold Star 31T Silicone	
							
Criteria	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Flexibility	35	3/5	21	4/5	28	5/5	35
Ease of Fabrication	30	4/5	24	4/5	24	2/5	12
Strength and Durability	15	5/5	15	4/5	12	3/5	9
Size Restriction	10	2/5	4	2/5	4	3/5	6
Price	5	3/5	3	3/5	3	2/5	2
Transparency	5	4/5	4	3/5	3	2/5	2
Total	100	71		74		66	

Criteria #1: Flexibility

This criterion evaluates the extent to which the selected material exhibits wall compliance sufficient to undergo visible and repeatable narrowing under transmural pressure during simulated forced expiration. This is a critical part of the material selection, as a component that is too rigid will fail to collapse at all, while one that deforms plastically will compromise the reproducibility of the flow-volume behavior across the testing the device must undergo. Therefore this criterion is weighted at 35. Design 3, Smooth-On Mold Star 31T Silicone, is scored at 5/5. Smooth-On Mold Star 31T Silicone is cast at a low shore hardness of 30A, giving it the lowest elastic modulus of the three candidates and the greatest capacity for smooth, reproducible collapse under low transmural pressures. Additionally, Smooth-On Mold Star Silicone's high elongation at break of 400% and strong elastic recovery after repeated deformation cycles, indicated by its 100% Modulus of 47 psi, make it the closest match to the compliance of a real airway wall [15]. Design 2, Flexible 50A, is scored at 4/5. Its lower shore hardness of 50A, 160% elongation at break, and rapid elastic springback make it substantially more capable of undergoing the visible, reversible deformation the flow-limitation mechanism requires [13]. Design 1, Flexible 80A, is scored at 3/5. While, it is marketed as one of the more flexible resins FormLabs offers, its shore hardness of 80A and comparatively high tensile strength of 8.9 MPa place it closer to a semi-rigid material rather than a compliant one [17].

Criteria #2: Ease of Fabrication

This criterion demonstrates how easily each material can be utilized to become part of the finished airway segment, given the fabrication resources available in the Wendt and Grainger labs and the time constraints of the project. This is an important consideration, as the device is single-use and must be produced within the project timeline. So, a material requiring excessive tooling, iteration, or manual post-processing introduces schedule risk, even if its mechanical properties are otherwise well suited. Therefore, this criterion is weighted at 30. Design 1, Flexible 80A, is scored at 4/5. As a resin compatible with the FormLabs Form 4 printers already available in the Design Innovation Lab, it can be printed directly from a CAD file [18]. Standard FormLabs post-processing, consisting of an isopropyl alcohol wash and UV post-cure, is well documented and fast, and the material's relative stiffness makes it less prone to print defects such as sagging or tearing during support removal [19]. Design 2, Flexible 50A, is scored at 4/5. It is also directly SLA-printable on the same Form 4 printers, preserving the single-step fabrication advantage of Design 1 [18]. However, its low durometer and tacky uncured surface make print handling and post-processing more delicate, since the supports are more difficult to remove cleanly without tearing the part, and through washing and post-curing are required to eliminate surface tackiness before the part is usable [19]. Design 3, Smooth-On Mold Star Silicone, is scored at 2/5. Unlike the two resin options, 31T Silicone cannot be 3D printed directly, and instead a mold must be fabricated. The outside of the mold will be designed using PLA, while the inner cylindrical mold will be made of PVA. Then, the silicone must be mixed, degassed to avoid trapped air bubbles that could compromise wall integrity, poured, and cured before the mold can be removed. The inner mold will be dissolved with a solution of H_2O , and then the 31T Silicone will be removed from the outer PLA mold [15, 16]. Each of the steps adds time and potential failure points, and any change to airway geometry requires a new or modified mold rather than a simple reprint.

Criteria #3: Strength and Durability

This criterion focuses on the ability of the airway material to withstand the necessary forces caused by simulated respiration and flow limitation, and to continue withstanding these forces over time such that it can be used for future demonstrations. It is important that the airway withstand respiration throughout testing, but since the end product will be used for a video demonstration, the durability is not crucial to the project's success. Because of these considerations, this criterion was given a weight of 15. Design 1, Flexible 80A, was given a rating of 5/5 due to its high tensile strength of 8.9 MPa and its reported durability throughout testing [11]. Design 2, Flexible 50A, was given a rating of 4/5. Its tensile strength of 3.4 MPa is lower than that of Flexible 80A, but still sufficient for the needs of this project, and it has a relatively high tear strength of 12.3 kN/m [13]. Design 3, Smooth-On Mold Star 31T, was given a lower rating of 3/5. Its tensile strength of 2.89 MPa is lower than that of both resin options, but its significant elongation at break of 339%, lower shore hardness, and 100% Modulus of 47 psi, allows for greater elasticity, demonstrating that it will better withstand repeated stresses over time [15].

Criteria #4: Size Restriction

This criterion evaluates the size constraints on each design due to their respective 3D printer buildable dimensions. Fabricating the device in multiple pieces and joining them together introduces unnecessary risk and may impact the flow of air through the tube, so it is crucial that the airway be fabricated in one solid piece. Additionally, having sufficient length is vital to ensure that the choke point movement distally through the airway is clearly visible. However, airway length is ultimately capped by the dimensions of the current vacuum box (203.2 mm × 203.2 mm × 203.2 mm), and because all candidate printer build envelopes either exceed this length or fall short by a minimal difference, the size constraints have a marginal effect on the actual size of the fabricated part. For this reason, the size restriction criterion was given a weight of only 10. Design 3, Smooth-On Mold Star 31T, was given a score of 3/5. While the material itself does not have any size constraints, the silicone will be set using a mold made of PVA, and this mold will be printed using the Ultimaker 3 Extended (Dual Nozzle) found in the Polymer Engineering Center on campus. The Ultimaker has a build envelope of 215mm by 215mm by 300mm, which is slightly larger than the Form 4 build envelope, yielding a slightly higher score [20]. Design 1, FormLabs Flexible 80A, and Design 2, FormLabs Flexible 50A, are both given a score of 2/5. Both would be fabricated using the Form 4 FormLabs SLA printer in the Design Innovation lab, which has a build envelope of 200mm by 125mm by 210mm [21].

Criteria #5: Price

This criterion evaluates how well each material fits within the proposed budget offered by our client of \$1,000. This budget includes costs associated with the project as a whole, and therefore includes the cost of potentially printing multiple iterations of the design as well as any supporting materials associated with using each material. This is an important consideration as it is a vital requirement that the project expenses do not exceed the budget, and a highly expensive material may limit the amount of testing and iterating the team is able to complete. While price is an important consideration, the overall budget is sizable and based on conversations with the client can be adjusted if necessary, so price is not the most major concern at this time. For these reasons, price is weighted at 5 within the design matrix. Designs 1 and 2, FormLabs Flexible 80A and Formlabs Flexible 50A respectively, are both available for printing through the Grainger Engineering Design Innovation Lab at Wendt Commons and are priced at \$0.29/g [20]. Both materials are therefore easily accessible

for printing as the team will not have to go through an outside vendor and are relatively inexpensive for printing a small-to-medium sized design, giving them both an equal score of 3/5. Design 3, the Smooth-On Mold Star 31T Silicone, was given the lowest score of 2/5 in this category. The silicone itself has an average price of \$0.04/g [14]. As part of the molding process, the team will also have to 3D print the molds for the silicone to fill in order to take on the shape of the airway. PLA, with a price of \$0.02/g, would be used to mold the outer diameter of the model, while dissolvable PVA, with a price of \$0.13/g, would be used to mold the inner diameter for easy removal [20, 22]. It is likely that the team will need to print a larger volume of material in order to create the mold than would be necessary if Flexible 50A or 80A were used to print the airway directly, and the projected learning curve for silicone molding creates a potential for wasted material that would increase cost. The higher volume of material required makes Smooth-On Mold Star 31T Silicone the most expensive proposed design option despite the lower cost per gram, yielding a lower overall score in this category.

Criteria #6: Transparency

This criterion evaluates the extent to which each material is truly clear, allowing choke points to be more visible as compression of all sides of the airway will be visible from a single angle. This is an important consideration as a more transparent material will assist the device in its main purpose of visibly demonstrating choke point movement, especially considering that this movement must be successfully captured on a video where multiple angles may not be available. While transparency is not a make-or-break factor in the design, the increased demonstrability that a more transparent material will give the model contributes to the weight of 5 of this category in the design matrix. Design 1, Flexible 80A, was scored a 4/5 in this category based on visual inspection on the FormLabs website and example prints available in the Design Innovation Lab at Wendt [12]. Design 2, Flexible 50A, was scored lower at 3/5 in this category based on similar inspection [11]. While both 50A and 80A are mostly transparent, when placed side by side with a similar device printed in 50A, it is apparent that 80A is noticeably clearer. Design 3, Smooth-On Mold Star 31T Silicone, scored the lowest at a 2/5 in this category. Visual inspection was performed on example molds created from the 31T Silicone similar to that performed on Flexible 80A and 50A. While the silicone was also transparent, the material was significantly more opaque than Flexible 80A or 50A, decreasing the overall score in this category [14].

Final Design Justification:

FormLabs Elastic 50A is the winning material across the six evaluated criteria. It is cost-effective and directly SLA-printable. This preserves the ease of fabrication of Flexible 80A while avoiding the time-constraint risk of silicone molding with 31T Silicone. Its low shore hardness and high elongation at break give it the flexibility needed to reproduce visible, repeatable airway collapse, an advantage that outweighs its lower strength and durability relative to Flexible 80A. Specifically, since the device is intended for a single video demonstration rather than long-term use. It also performs adequately on size restriction and transparency, with no significant weaknesses to offset its strong performance in the two most heavily weighted criteria. Overall, all three materials were viable options for the airway component, but Flexible 50A best balances compliance and fabricability for this project's needs.

Airway Preliminary Designs

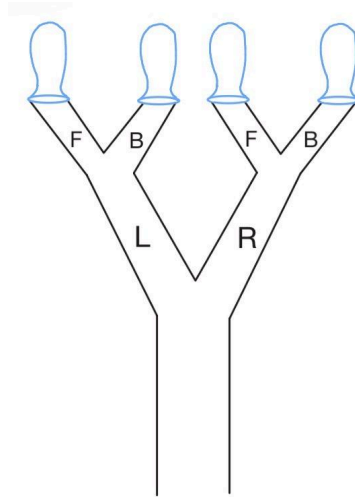


Figure 4: Symmetric Model Depiction. In this model, L is the left bronchus, R is the right bronchus, and F and B are the daughter branches at the subsequent bifurcation.

The Symmetric Model used is based on Weibel's morphometric model of the lung, which defines specified branching ratios from generation to generation, and represents the left and right airway trees as geometric mirrors of one another [23]. The greatest strength of this model is the ease of SolidWorks modeling and manufacturing, since both sides of the airway share the same dimensions, substantially reducing design and fabrication complexity. A major drawback of this model is the physiological inaccuracy, since the dimensions and branching distribution of the left and right sections of a human airway differ and are not symmetrical [23]. Additionally, the literature supporting this design does not include all of the necessary information for full 3D reconstruction, such as branching angles and rotational orientation between generations, and characterizes only the first few generations which does not extend to the region flow limitation occurs [23].

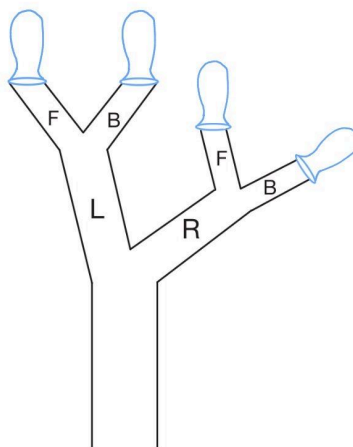


Figure 5: Asymmetric Model Depiction. In this model, L is the left bronchus, R is the right bronchus, and F and B are the daughter branches at the subsequent bifurcation.

The Asymmetric Model is based on Weibel's morphometric model of the lung and has been modified by Liu et al. to account for physiological asymmetry between the left and right airway sections [23, 24]. Rather than treating the two airway sections as mirror images, this model applies differing branching ratios to each side, reflecting the known anatomical divergence between the left (L) and right (R) bronchial trees, as illustrated in Figure 2. The asymmetric design more accurately represents airway geometry, which aids in the modeling of flow limitation and learner comprehension. This design is also able to be modeled and manufactured relatively easily. The major limitation of the Asymmetric Model is the limited branching generation and angle literature to support the dimensions needed for the modeling [24].

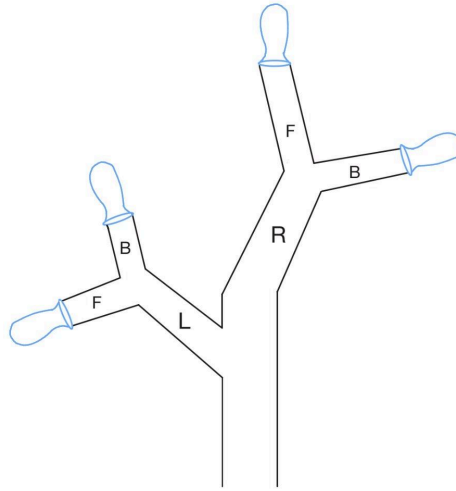
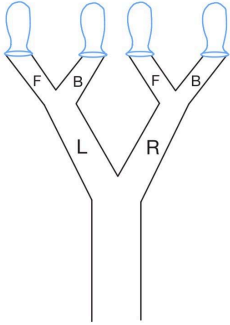
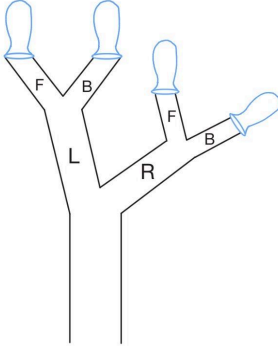
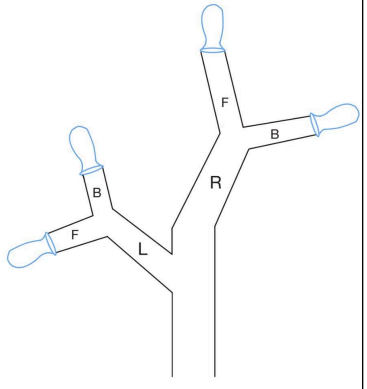


Figure 6: Stochastic Model Depiction. In this model, L is the left bronchus, R is the right bronchus, and F and B are the daughter branches at the subsequent bifurcation.

The third design is the Stochastic Model, modeled by Hoffman, which introduces a degree of randomness to generate the branching angles, diameter, and length of the bifurcations within the airway [23]. This model generated a large data set with the necessary information to create a physiologically accurate model by modeling the correct region where flow limitation occurs, and accounting for the natural irregularities found in the human airway [23]. The primary limitation of this model is increased manufacturing and modeling difficulty, due to each branch having slightly different dimensions. This variability will require more careful, branch-by-branch modeling in SolidWorks, and could introduce additional issues in the fabrication of the airway.

Table 2: The design matrix for modeling airway choices

		Design 1: Symmetric Model		Design 2: Asymmetric Model		Design 3: Stochastic	
							
Criteria	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Physiologically Accurate	30	2/5	12	4/5	24	5/5	30
Manufacturing Feasibility	20	5/5	20	4/5	16	3/5	12
Modeling Feasibility	20	5/5	20	4/5	16	3/5	12
Supported Literature	15	1/5	3	2/5	6	5/5	15
Pathological Adaptability	10	3/5	6	3/5	6	4/5	8
Durability	5	5/5	5	3/5	3	3/5	3
Total	100	66		71		80	

Criteria #1: Physiologically Accurate

This criterion evaluates the ability of the model to physiologically match the dimensions of the human body. Physiologically accurate geometry is not only beneficial for learners to understand anatomical correctness, but also for generating a more precise flow limitation. Airway dimensions vary across individuals, so an accurate model should also strive to represent as broad and inclusive a population as possible rather than a single fixed anatomy. Due to the importance of this accuracy needed for teaching and modeling flow limitation, this criterion is weighted at 30. Design 3, the Stochastic Model, received a 5/5, as the asymmetry and random nature of the branching closely approximate the physiological bifurcations of the airway [23]. The Stochastic Model also captures the difference between the anatomically asymmetrical right and left halves of the airway more accurately than the fixed geometric ratio [23]. The randomness also allows the model to represent a broader population of people, since specific airway dimensions differ from person to person. Design 2, the Asymmetric Model, earned a 4/5, as it encompasses some aspects of the physiological airway with unequal

branching angles and dimensions between the right and left sections of the airway, but lacks the irregular ratios present between successive generations of bronchioles [23]. Design 1, the Symmetric Model, oversimplifies the airway geometry and does not account for the differences in distribution and dimensions of the left and right sections of the airway, and for this reason, the Symmetric Model received a 2/5.

Criteria #2: Manufacturing Feasibility

Manufacturing feasibility is weighted at 20, because the airway model needs to be physically manufactured successfully for the final device to function as intended. A design that cannot be manufactured efficiently or accurately would be impractical for the project timeline, even if it outperforms alternative designs in other criteria. The three airway designs differ in how easily they can be manufactured, as branch density and orientation directly affect manufacturing complexity. Higher branch density and more pronounced directional variation can produce sharper angles and undercuts, which may require the model to be fabricated in multiple sections[25]. Design 1, the Symmetric Model, received a 5/5, because its branches have more consistent spacing and orientation which simplifies the manufacturing process. Design 2, the Asymmetric Model, received a score of 4/5, as it has varying branch angles and positions which introduces moderately greater manufacturing complexity relative to the Symmetric Model. Design 3, the Stochastic Model, is the most complex of the three, due to its irregular branching geometry, giving it the score of 3/5. As the branches converge more closely together and their orientations shift further inward or outward, sharper angles and undercuts are more likely to form requiring the model to be divided during manufacturing [25].

Criteria #3: Modeling Feasibility

Modeling feasibility is weighted at 20 because creating an accurate and functional SolidWorks model is necessary before the airway can be manufactured and tested. A design that is too difficult or time-consuming to model could hinder the team's ability to modify the geometry and meet client requirements. The three airway designs will vary in how they can be modeled in SolidWorks, making it important to assess the relative modeling feasibility of each. Previous airway modeling research found that digital modifications will be necessary when the original geometry creates difficulties, including cutting an open channel into the airway model [26]. Design 1, the symmetric design, received a 5/5 because its four branches uses more consistent dimensions, angles, and repeated features, thus making the model easier to create and modify. Using individual airway models allows changes to be made to more specific parts of the model without having to redesign the entire prototype [26]. Design 2, the asymmetrical design, received a score of 4/5, as its varying branch angles and positions require more individually defined dimensions and, consequently, more elements to be modified within SolidWorks. Design 3, the stochastic design, contains the most irregular branch arrangement and would require the greatest number of geometric modifications; when modeling complex airway geometries, accurately and digitally replicating and assembling the structure requires additional revisions and testing [26]. For this reason, the stochastic design received a score of 3/5, reflecting the added time and difficulty associated with its branch complexity.

Criteria #4: Supported Literature

The mathematical dimensions of the airway model should be supported by previously completed studies to ensure anatomical compliance and modeling accuracy. This criterion is weighted at 15, as closely mirroring established airway dimensions is necessary to accurately model flow limitation, and prior studies provide a

stronger basis for dimensional accuracy than assumed or estimated values. Design 3, the Stochastic Model, scored a 5/5 for this criterion, as its supporting literature provides branching angles, diameters, and lengths across a large number of bifurcation generations [23]. The information provided in the diverse data set can allow accurate modeling of different regions of the airway to model flow limitation. Design 2, the Asymmetric Model, earned a score of 2/5, while it is defined across multiple generations, this coverage does not extend to the same degree as the Stochastic Model, and the underlying data does not capture changes in branching angle [24]. Design 1, the Symmetric Model, is a fundamental model that has been used in many subsequent studies [23]. The model is limited to the first five bifurcations, which is not the accurate airway region for flow limitation, and also does not include the necessary branching angles that would affect airflow [23]. Due to these limitations, the Symmetric Model received a score of 1/5.

Criteria #5: Pathological Adaptability

This criterion focuses on the ability of the models to represent the bronchioles of a human and its ability to accurately represent the presence of diseases that are linked to having an effect on flow limitation. It is weighted at 10 because although it is an important aspect in educational terms, the client did not specifically request that the model represents more than a normal set of airways. Design 3, the Stochastic Model, received a 4/5 because of the realistic pulmonary representation of disease such as ARDS, emphysema, and idiopathic pulmonary fibrosis, creating unpredictable and random distributions of flow and pressures. Irregular bronchiole length and changing subcardinal angles makes the Stochastic Model the most adaptable to model complex diseased airways [27]. Design 1, the Symmetric Model, is based on geometrical branching with identical dimensions that split airway flow and pressure evenly throughout. This baseline model cannot inherently display the effects of diseases; hence, receiving a 3/5. This symmetrical design is commonly used with symmetrical dichotomous branching to get baseline flow rates and uniform fluid dynamics [28]. Design 2, the Asymmetric Model, also received a 3/5 because it does a better job incorporating anatomical imbalance through varying branch length and bifurcation angles, which can display pressure imbalances. This model also better represents realistic branching ratios and varying ventilation which are both crucial to survival [29]. However, its limitation lies in the fixed asymmetry instead of a dynamic representation of disease.

Criteria #6: Durability

Durability evaluates the design and its structural integrity, pressure resistance in a vacuum chamber and its longevity. Because this device will be displayed using a video demonstration, durability is a minor consideration, resulting in a weighting of 5. Design 1, the Symmetric Model, scored the highest with a 5/5 because of its geometric ratios and consistent branching. This creates even pressures throughout and reduces strain on branch joints. It also reduces the chance of high pressure points forming and cracking during repeated testing. Design 2, the Asymmetric Model, scored a 3/5 because it introduces asymmetric branching and bronchial lengths. This forces air pressures to push unevenly along the airways which creates issues that interfere with a need for thicker walls versus the realistic ratio between lumen opening and the wall thickness dimension. Design 3, the Stochastic Model, also scored a 3/5 because it carries the highest risk of failure due to its total randomness and irregular branching. These can create weak seams during manufacturing and high stress points which are far more likely to cause damage under repeated testing pressure cycles. This criterion is weighted at only 5, because although the integrity of our model is important, the dimensions of the models will be fairly consistent regardless and we are confident in the strength of the materials at the desired dimensions.

Final Design Justification

The winning design is the Stochastic Model. This design scored the highest in three of the six criteria categories. Physiological accuracy is the most important aspect of the design to accurately model flow limitation, both with seeing the choke points and the correct anatomy for the learners to see. This design also has the most supportive literature which will ensure the dimensions are comparable to the human airway and has the data to support the necessary dimensions such as branching angles and particular further generations that are closer to where flow limitation occurs. The stochastic design also has the highest pathological adaptability to model pulmonary diseases which could be explored in the design to increase academic relevance.

Alveoli Preliminary Designs



Figure 7: Depiction of Water Balloons [30]

Water balloons are typically manufactured from natural rubber latex to enhance elasticity and flexibility [31]. Their thin walled latex geometry allows them to stretch and inflate easily under low air pressures [31]. The compact size and narrow neck make them aesthetically similar to alveoli and have a convenient fitting over the bronchial attachments. Because the thin material is engineered to tear or pop under stress, these balloons have a lower overall durability and higher likelihood of bursting during the testing process [31]. Water balloons would be easy to obtain as the team can be quickly ordered online in large quantities or purchased at retail stores for low prices.



Figure 8: Depiction of Latex Balloons [32]

Latex balloons are made from natural rubber and are one of the most common and affordable types of balloons available [33]. Latex is also highly stretchable, allowing the balloons to expand and change when they are inflated [33]. This elasticity could make the latex balloon useful for modeling the expansion and contraction of the alveoli during flow limitation. Latex balloons are available in many sizes and can be easily inflated with air, making them a practical option for the airway model. It is important to note that latex is sensitive to friction, heat, and time, which may affect the balloon's durability during the testing process [33].

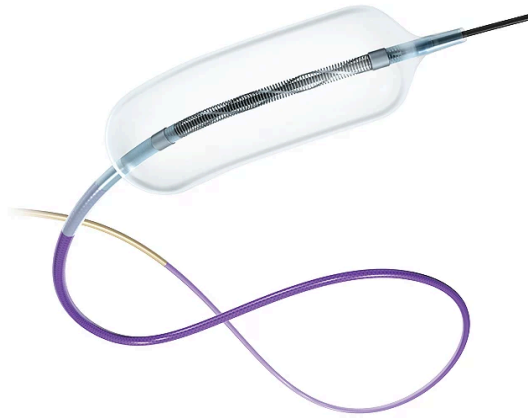
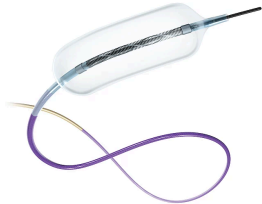


Figure 9: Depiction of Stryker Transform Occlusion Balloon Catheter [34]

The Stryker TransForm is specifically designed for use in medical devices and catheter-based applications [35]. They are available in three different design types: compliant, semi-compliant, and non-compliant [35]. For this design, a compliant medical balloon would be useful because it can expand when pressure is applied, allowing it to model the expansion and contraction of alveoli. This design could provide a more controlled and realistic representation of alveoli expansion, although the nature of the medical-grade balloon may make it more expensive or difficult to obtain.

Table 3: The design matrix for modeling alveoli choices

		Design 1: Water Balloons		Design 2: Latex Balloons		Design 3: Stryker Transform Occlusion Balloon Catheter, Super Compliant	
							
Criteria	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Connection Points	30	4/5	24	2/5	12	5/5	30
Elasticity	25	4/5	20	2/5	10	5/5	25
Durability	25	3/5	15	4/5	20	2/5	10
Price	15	5/5	15	4/5	12	1/5	3
Size	5	5/5	5	3/5	3	4/5	4
Total	100	79		57		72	

Criteria #1: Connection Points

This criterion evaluates how easily and reliably each balloon type can be attached to the bronchi of the airway model, considering the geometry, thickness, and consistency of the balloon's neck. Since a poor or inconsistent connection risks air leakage, premature detachment during testing, or an event where the balloon's neck cannot accommodate variation in the diameter of the bronchus, the criterion is weighted at 30. Design 1, Water Balloons, is scored at 4/5. Water balloons have a short, narrow neck with a relatively thick, consistent wall, giving it a snug, predictable fit when stretched over the bronchi. Because the neck is short and uniform, it can be quickly secured with a simple tie, a small clamp, or minimal adhesive [36]. This makes it efficient to attach and reposition across multiple bronchial branches, although the small neck diameter does limit how large a fitting it can accommodate. Design 3, the Stryker TransForm, is scored at 4/5. The Stryker TransForm are manufactured to tight dimensional tolerances with necks specifically designed for secure attachment to tubing fittings. However, the neck of the Stryker TransForm is comparably smaller than the dimensions of the airway geometry of the 3D model. While there are adapters to create a smooth connection between the 12.7 mm to 25.4 mm opening of the 3D-modeled bronchi and the 0.36 mm opening of the Stryker TransForm balloon, it would introduce another complication into the design. Design 2, Latex Balloons, is scored at 2/5. While the longer neck offers more surface area to work with, its thinness and higher elasticity make the fit less predictable. The connection points of the Latex balloon's 12.7 mm to 19.05 mm neck may stretch unevenly when being fitted

over the bronchi, giving it the tendency to slip or loosen with handling, and its variable thickness from balloon to balloon makes achieving a consistent, airtight seal across multiple connection points more difficult [37, 47].

Criteria #2: Elasticity

This criterion evaluates how easily the balloon material stretches and how similar its elastic characteristics are to those of anatomical alveoli. The elasticity of alveoli is a key factor in generating accurate movement of the choke point, because as alveoli volume decreases during expiration, their elastic recoil pressure drastically drops, resulting in a pressure differential that causes the choke point to move distally [38]. Without this drop in elastic recoil pressure throughout expiration, the choke point will not move. Therefore, this criterion was given a relatively high importance of 25. Design 3, the medical grade balloon, ranked highest at 5/5. According to ISO 10555-4, catheter balloons categorized as “super-compliant” are designed with extremely high elasticity in order to expand easily at a very low expansion pressure [39]. The Stryker TransForm is designed to expand predictably and uniformly with no high initial resistance [40]. In contrast, Design 1, the water balloon, exhibits non-linear elasticity with a very high initial inflation pressure [41], making its performance less anatomically accurate. However, while nonlinear, the elasticity characteristics of water balloons are sufficient to create the pressure differential needed for choke point movement, resulting in a rating of 4/5. Design 2, the latex balloon, also exhibits non-linear elasticity and a high initial inflation pressure, and its slightly lower elasticity compared to Design 1 results in a ranking of 3/5.

Criteria #3: Durability

This criterion impacts device function and longevity. Balloon durability is an important concern as any damages to the balloons would disrupt airway seals, rendering the device unusable. The balloons must be able to handle repeated pressure differentials causing inflation and deflation as well as abrasion around the connection points to the bronchi of the airway model without rupturing. This category is therefore weighted at 25 to account for the importance of balloon durability to the success of the project. Design 2, Latex Balloons, is scored at a 4/5. The natural latex material and thicker balloon walls contribute to a higher tear resistance, ability to deal with higher pressures without bursting, and resistance to abrasion, increasing overall durability. Design 1, Water Balloons, is scored at 3/5. Most water balloons on the market are made of natural latex, which is rated highly for tear resistance [31, 42]. However, water balloons tend to be thinner and are purposefully designed to burst more easily than normal latex balloons and are therefore rated lower in the durability category. Design 3, the Stryker TransForm, is scored at 2/5. Compliant medical-grade balloons such as those utilized in catheter-based applications are designed for use in a low-pressure environment and tend to have a lower burst pressure than other types of balloons, decreasing their overall durability rating [43].

Criteria #4: Price

The cost of the balloon varies between the different types of balloons. To be able to fit in the budget of \$1000 for materials the client has provided and obtain the other necessary materials to model the airway, while obtaining at least 4 of the balloons for the final product as well as some extra balloons for testing, the cost of each balloon should be relatively low. The water balloons scored highest of a 5/5 in this matrix as they are the least expensive balloon option and are readily available, allowing for less competition in price [44]. Latex balloons received a score of 4/5 because they still have a relatively low cost, but are slightly more expensive than the water balloons [45]. These balloons are also easily found, which keeps the competitive price low. The

medical grade balloons received the lowest score of 1/5. This is due to the fact that most balloons are sold in a catheter balloon system and are unable to be purchased on their own or are used sparingly and thus there is more competition for the price [46]. The extra materials that accompany the balloons and difficulty in availability of the medical grade balloons cause the increased price and contribute to the low score for this design.

Criteria #5: Size

This criterion assesses the general size representation of the balloons and their physiological accuracy relative to the dimensions of the airway model. This criterion is weighted at only 5, as size representation is a secondary consideration relative to function performance. A minor deviation in balloon dimension does not compromise the model's ability to simulate flow limitation or airway collapse, and any size discrepancy can be partially offset through calibration of inflation pressure or tubing diameter during testing. Design 1, Water Balloons, received the highest score of 5/5, due to their accurate anatomical representation and its assumed compatibility to the airway model. These balloons when inflated are around 12.7-15.2 cm in size and 7.62 cm when deflated with around an 1.27 cm stretchy latex opening [44]. Design 3, the Catheter Balloon, received a 4/5 due to their smaller size. With an inflated size of around 7 mm by 7 mm, these balloons do not create an accurate size representation in proportion to the size of the airway model [47]. Design 2, Latex Balloons, scored 3/5 due to its comparatively large size of around 30.48 cm when fully inflated. Assuming they inflate anywhere close to their max inflation, these balloons will not only be misproportionate but they will also take up too much space and be a poor representation of realistic dimensions. While these balloons are deflated they are around 10.2 to 12.7 cm which is also too large and a poor representation of the correct anatomy [45].

Final Design Justification

The winning design is the water balloons because they provide the best overall balance of connection points, elasticity, durability, price, and size of the airway model. Even though the medical-grade balloons scored higher in the connection points and elasticity, their higher cost and lower durability and smaller size make them less practical for the final design. Latex balloons offered a better durability than the water balloons, but their larger size and connection point reliability make them less accurate for modeling the alveoli. Water balloons provide secure connection to the bronchial tubing section and sufficient elasticity to create pressure changes needed to model the alveoli behavior. The low cost and availability allow the team to purchase additional balloons for testing and replacement if needed. All in all, the water balloons offer the most practical combination and are the most suitable choice for the airway model.

Proposed Final Design

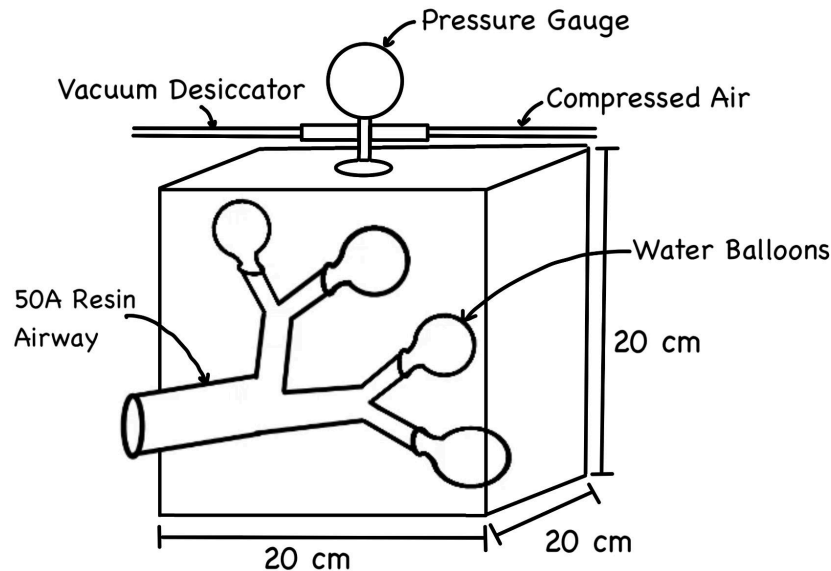


Figure 10: Proposed Final Design Depiction

The proposed final design is a $20 \times 20 \times 20$ cm sealed chamber housing a branching airway model, shown in Figure X. The airway follows the stochastic model and is 3D-printed from Formlabs Elastic 50A. It extends from the lower trachea through successive bifurcations, and a water balloon at the end of each terminal branch represents an alveolar compartment. The open tracheal end exits the chamber, so the airway interior is exposed to atmospheric pressure while the surrounding chamber pressure can be controlled independently. This arrangement allows the chamber pressure to represent the pleural pressure acting on the airway during breathing.

Compressed air and vacuum lines connect to the top of the chamber through a shared manifold fitted with a pressure gauge. During the demonstration, compressed air raises the pressure inside the chamber, simulating the rise in intrathoracic pressure during forced expiration. As this external pressure increases, the airway walls are compressed wherever the pressure inside the airway falls below the pressure outside it. Because the pressure within the airway decreases along its length as air flows from the balloons toward the open end, the compression begins downstream, where the equal pressure point forms, and a choke point develops. The vacuum line, supplied by a vacuum desiccator acting as a reservoir, lowers the chamber pressure to return the airway to its uncompressed state between trials and to allow the compression to be repeated reproducibly. The pressure gauge displays the chamber pressure throughout, so the applied pressure can be linked to the degree of airway collapse.

Fabrication

Materials

The branching airway model will be fabricated using FormLabs Flexible 50A Resin, a material that was chosen based on its high elasticity, adequate tensile strength, and availability at [13]. The alveoli will be modeled using small latex water balloons, which have sufficient elasticity to create the high pressure needed for choke point formation. Finally, pleural pressure will be simulated using the vacuum box obtained by the previous project, which is composed of 20mm-thick pressure-resistant acrylic [48] and includes a gauge to measure internal pressure. The internal pressure will be created through the combined effects of a vacuum desiccator and a compressed air source.

Methods

The team will begin with designing the airway in SolidWorks according to the dimensions outlined by the stochastic model [23]. The part file will be uploaded into the Preform slicing software to be compliant with the necessary input type, .form, for the FormLabs Form 4 3D printers in the Grainger Design Innovation Lab at Wendt. A request will be submitted to the staff at the Grainger Design Innovation Lab at Wendt to fulfill the 3D printing order, and once the prototype has been printed and received, post-process techniques including removal of supports and finishing of the prototype will be completed. Following the completion of the airway print, the alveoli-modeling water balloons will be attached to the airway using cyanoacrylate. See Appendix B for detailed fabrication protocol. The airway and alveoli device will then be inserted into the pressure vessel and will be secured to the vessel by tape for testing. Once a final prototype has been established, silicone caulk will be used to adhere the airway model to the box. The pressure vessel will be connected to a vacuum desiccator and a compressed air source.

Testing and Results

Alveoli Balloon Testing

The added pressure difference created by the expansion of the alveoli is essential to creating the choke points and is vital to the modeling of this project. Compliance of the water balloons affects the expansion of the balloons and may be close to physiological internal pressure of the alveoli of about +130 cm H₂O which includes the pleural pressure and elastic recoil pressure [49]. The pressure inside the water balloons will be determined by continuous measurement with a BMP388 barometric pressure sensor.

A water balloon will be inflated with air using a handheld balloon pump to model the expansion of the lung during forced exhalation. A BMP388 barometric pressure sensor will be connected to an Arduino Uno using a STEMMA QT/Qwiic cable with 4-pin male header connectors, powered at 3.3 V (Vin). The Arduino will simultaneously be connected to a computer running the Arduino IDE (Figure 11).

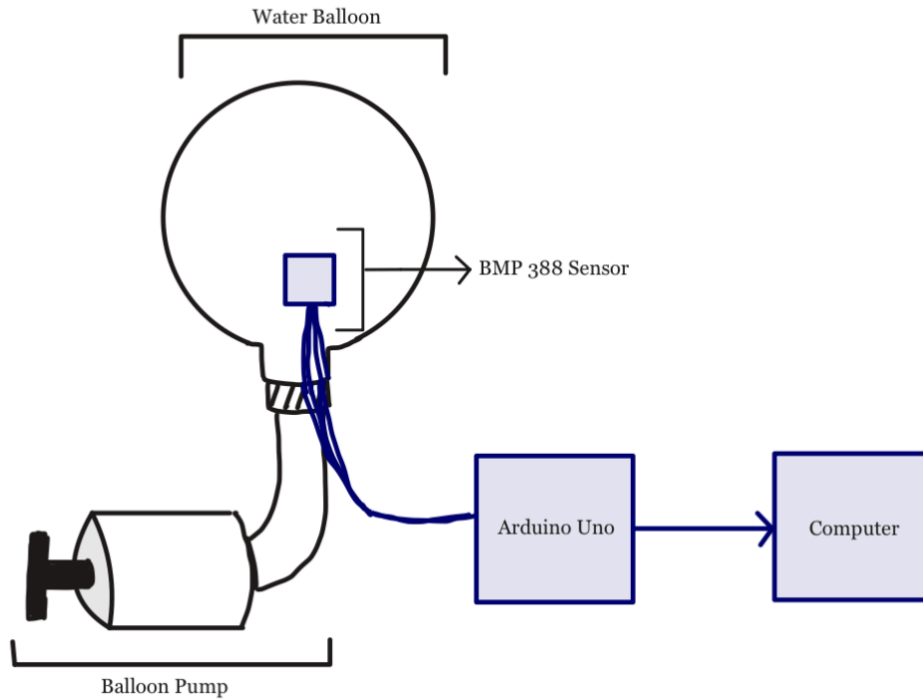


Figure 11: Depiction of the set-up of measuring pressure inside an inflating water balloon using a BMP388 Sensor.

The sensor will be sealed within the balloon, and no more than four balloon pump strokes will be delivered, so that the balloon does not rupture. Each consecutive balloon pump stroke is meant to simulate a prolonged forced exhalation [50]. No more than four balloon pump strokes will be delivered, so that the balloon does not rupture. Pressure will be acquired through the Adafruit BMP3XX library, with absolute readings (Pa) returned by the *bmp.pressure* call following each *bmp.performReading()* command. A baseline atmospheric reading outside the water balloon will be recorded before inflation so that readings can be converted to gauge pressure using Equation X:

$$P_{gauge} = P_{abs} - P_{atm} \quad (X)$$

The resulting pressure-time profiles will be used as input boundary conditions for a 3D model of the airway, in which flow limitation during forced expiration will be simulated.

Airway SolidWorks FEA Testing

A model of the airway prototype will need to be developed in SolidWorks as a part of the 3D printing preparation process. Simulations can be run within the SolidWorks interface with the Simulation add-in enabled in Tools. Geometry and material properties will be applied to the model and boundary conditions will be applied that define fixtures and pressures that will match our testing conditions. After applying meshing, the simulation

can be run and will allow for visualization of where the choke points may form through the metric of failure points.

Airway Comparison Testing

The team will print a sample tube with the same wall thickness and dimensions of the main bronchus of the airway to complete MTS testing. Additionally, the team will replicate the dimensions and wall thickness of the first tube of the printed airway from last year's project. The MTS machine will be set up using 2kN Advantage Screw Action 2000 Grips in the Clevis to be able to adequately hold the tubing in the machine. The tubing will be inserted into both grips and the test will be run until there is noticeable failure in the tubing. Data will be collected and analyzed to create a stress strain curve to determine values for Young's modulus and tensile strength of each sample tube. The tube sample from the previous team's design will be compared to the current team's model to get a benchmark for how compliant the team's design is in comparison to the previous team's design which did not accurately model the choke points.

Simulated Forced Expiration

Once the first prototype has been assembled, the team will begin testing the prototype in the pressure chamber. The 3D printed airway and alveoli assembly will be inserted into the pressure chamber with the vacuum desiccator and compressed air connected, but the valves closed. Once setup is complete, the valves for the vacuum desiccator and compressed air will be opened and a pressure difference will occur. If the model is successful, a choke point will be created and move distally. A video recording will be used to ensure capturing of the created choke point and the distal movement. Quantitative measuring of the narrowed diameter of the choke point versus the initial diameter will be done in ImageJ and a qualitative recording of whether or not the choke point moved distally will also be recorded. A successful choke point creation will be signified by a decrease in diameter of the airway by at least 50%. Additionally, pressure values from the pressure gauge will be recorded to determine if there is a threshold pressure that causes the choke points to form and move distally. The simulated force expiration will be run at least 10 times to ensure accurate capturing of data, and allow for statistical analysis.

Discussion

The major final deliverable for this project is a 6-10 second video of the model demonstrating choke point formation and movement. As such, the team will be the main users of the device; however, user safety remains a major ethical consideration when designing and fabricating this device. The team will follow compressed air guidelines as outlined in OSHA standard 1910.243(b) [51] and will avoid using any toxic materials during the fabrication of the device.

While material testing will be beneficial in determining model compliance in support of choke point formation before final simulated forced expiration testing occurs, complications may arise as part of the fabrication process. A major point of difficulty will be support removal within the 3D printed model, especially given that the airway will be a thin-walled hollow branching tube of varying diameter. The team will take care

to avoid damaging the model during support removal and will follow recommended post-processing techniques to ensure a relatively smooth interior finish in the final model.

Given testing results, the team will evaluate whether or not the completed device adequately demonstrates choke point formation and movement through the airway model. While the previous model did not demonstrate this phenomenon in a manner sufficient for the client's purposes, the aforementioned compliance testing of the previously designed bronchi model will provide important benchmarks for the new model to improve upon. The team can complete the airway comparison testing procedure throughout the prototyping phase to demonstrate whether or not the new design successfully passes this compliance benchmark set by last year's team; a lower compliance in the bronchi in the new model compared to the previous model will demonstrate progress towards choke point formation as the design process continues. Additional mathematical models factoring in variables such as tube thickness, length, and elasticity, will further support design choices in the SolidWorks bronchi model and the 3D printed prototype.

Based on compliance testing results and mathematical model input, the team will ensure that the final design is compliant enough for visible choke point formation and movement, which will be verified through the simulated forced expiration testing. Individual testing results will be evaluated to determine which, if any, factors prevent choke point formation. The internal pressure from the alveoli balloon testing can be plotted against diameter of the balloon to inform the team of how multiple inflations can change pressure to see if that affects whether or not choke points form in the airway. The SolidWorks FEA visualization can be compared to the simulated force expiration testing. This can allow the team to see potential limitations of the airway model compared to the simulated testing to identify discrepancies between models that could affect choke point formation. If necessary, changes will be made to the design regarding airway wall thickness and material properties, alveoli balloon elasticity, model dimensions, and/or alveoli-bronchi connection techniques to ensure that the final design visibly demonstrates the choke point formation.

Conclusions

In summary, this project presents a physical teaching model designed to demonstrate flow limitation, the equal pressure points (EPP), and the distal movement of choke points during forced expiration. While flow limitation is prominent in obstructive airway diseases, it also occurs in healthy individuals at a lower rate, making it critical in understanding both normal and pathological airway mechanics. The final design demonstrated stochastic branching airway models based on the Hoffman geometry, 3D-printed from compliant Formlabs Elastic 50A resin [13]. The alveolar compartments are modeled using thin-walled natural water balloons attached at the terminal bronchial ends. The full model is housed inside a sealed acrylic vacuum box controlled by compressed air and vacuum lines to simulate changing pressures.

The stochastic airways design was selected because its irregular branching angles, lengths, and diameters more closely represent the variability of the human airway anatomy than symmetric or asymmetric alternatives. Formlabs Elastic 50A was selected for its flexibility and ease of fabrication and water balloons were selected because they provide an accessible and cost-effective way of representing the elastic behavior of the alveoli. Together, these components are going to produce visible airway compression and demonstrate how the location of flow limitation can change as pressure conditions vary.

Future work will focus on fabricating an airway model prototype to understand the pressure and elasticity of the water balloons, and evaluating the airways mechanics through SolidWorks. The completed model will then undergo repeated simulation of forced expiration in the pressure chamber to determine whether or not the airway reaches its 50% reduction in diameter and properly demonstrates the distal movement of the choke point. If the behavior is not observed, adjustments to the airway thickness, material properties, balloon elasticity, or the connections between the airway and alveoli may be necessary. Successful completion of these tests will then allow for the creation of a short and educational video to help medical students and fellows better understand flow limitation and its relationship with obstructive airway diseases.

References

- [1] C. Tantucci, “Expiratory Flow Limitation Definition, Mechanisms, Methods, and Significance,” *Pulm Med*, vol. 2013, p. 749860, 2013, doi: 10.1155/2013/749860.
- [2] M. Abrami et al., “Mucus Structure, Viscoelastic Properties, and Composition in Chronic Respiratory Diseases,” *Int J Mol Sci*, vol. 25, no. 3, p. 1933, Feb. 2024, doi: 10.3390/ijms25031933.
- [3] F. Jiang, T. Hirano, C. Liang, G. Zhang, K. Matsunaga, and X. Chen, “Multi-scale simulations of pulmonary airflow based on a coupled 3D-1D-0D model,” *Computers in Biology and Medicine*, vol. 171, p. 108150, Mar. 2024, doi: 10.1016/j.compbiomed.2024.108150.
- [4] “Computational Model for Forced Expiration from Asymmetric Normal Lungs | *Annals of Biomedical Engineering* | Springer Nature Link.” Accessed: Sep. 16, 2026. [Online]. Available: <https://link.springer.com/article/10.1114/1.1588651>
- [5] M. M. de Oca et al., “The global burden of COPD: epidemiology and effect of prevention strategies,” *The Lancet Respiratory Medicine*, vol. 13, no. 8, pp. 709–724, Aug. 2025, doi: 10.1016/S2213-2600(24)00339-4.
- [6] “Spirometry - an overview | ScienceDirect Topics.” Accessed: Oct. 03, 2026. [Online]. Available: <https://www.sciencedirect.com/topics/medicine-and-dentistry/spirometry>
- [7] A. Binks, “Pulmonary Physiology for Pre-Clinical Students,” Jun. 2022, doi: 10.21061/pulmonaryphysiology.
- [8] M. S. Zach, “The Physiology of Forced Expiration,” *Paediatric Respiratory Reviews*, vol. 1, no. 1, pp. 36–39, Mar. 2000, doi: 10.1053/prrv.2000.0010.
- [9] B. Kuhn and I. Barjaktarevic, “Editorial: Understanding the Impact of Lung Ventilation Heterogeneity,” *Frontiers in Medical Technology*, vol. 6, Mar. 2024, doi: 10.3389/fmedt.2024.1332958.
- [10] R. Kumar, S. Kumar, S. Soni, D. Kumar, and R. Raman, “Human Trachea and Bronchi: Structural Adaptations in Respiratory Health,” *Bioinformation*, vol. 22, no. 6, pp. 3264–3267, Jun. 2026, doi: 10.6026/973206300223264.
- [11] “Flexible 80A Resin | Flexible Resin 3D Printing Material,” Formlabs. Accessed: Sep. 24, 2026. [Online]. Available: <https://formlabs.com/products/flexible-80a-resin-v1/>
- [12] “Using Flexible 50A Resin,” Formlabs. Accessed: Sep. 24, 2026. [Online]. Available: <https://formlabs.com/support/Using-Elastic-Resin/>
- [13] “Flexible 50A Resin | Formlabs.” Accessed: Sep. 24, 2026. [Online]. Available: <https://formlabs.com/products/flexible-50a-resin/>
- [14] “Mold Star®; 31T.” Accessed: Sep. 24, 2026. [Online]. Available: <https://shop.smooth-on.com/mold-star-31t>

- [15] “Mold Star™ 31T Product Information,” Smooth-On, Inc. Accessed: Sep. 24, 2026. [Online]. Available: <https://www.smooth-on.com/products/mold-star-31t/>
- [16] N. Q. Vu, T. M. Le, A. N. B. Ngo, M. H. T. Nguyen, Y.-C. Liao, and T. T. Tran, “Engineering Functional PVA: A Comprehensive Review of Chemical Modifications and Prospective Developments,” *ACS Polym Au*, vol. 6, no. 1, pp. 33–60, doi: 10.1021/acspolymersau.5c00133.
- [17] “Using Flexible 80A Resin,” Formlabs. Accessed: Sep. 24, 2026. [Online]. Available: <https://formlabs.com/support/Using-Flexible-Resin/>
- [18] “making.engr.wisc.edu/equipment/3d-printers/.” Accessed: Sep. 23, 2026. [Online]. Available: <https://making.engr.wisc.edu/equipment/3d-printers/>
- [19] “3D Printing Guide: Types of 3D Printers, Materials, and Applications,” Formlabs. Accessed: Sep. 23, 2026. [Online]. Available: <https://formlabs.com/3d-printers/>
- [20] “Additive Manufacturing,” Polymer Engineering Center. Accessed: Sep. 24, 2026. [Online]. Available: <https://pec.engr.wisc.edu/additive-manufacturing/>
- [21] “3D Printer Dimensions,” Google Docs. Accessed: Sep. 24, 2026. [Online]. Available: https://docs.google.com/spreadsheets/d/125EWYr0aojDuu0BGfzzt-YhfGJA1wojkzE-Vt00tw_M/edit?gid=0&usp=embed_facebook
- [22] “UltiMaker PVA Filament Natural (0.75kg, 1.65lb).” Accessed: Sep. 24, 2026. [Online]. Available: <https://store.ultimaker.com/pva-m0952-natural-750-206127>
- [23] K. Ahookhosh, O. Pourmehran, H. Aminfar, M. Mohammadpourfard, M. M. Sarafranz, and H. Hamishehkar, “Development of human respiratory airway models: A review,” *European Journal of Pharmaceutical Sciences*, vol. 145, p. 105233, Mar. 2020, doi: 10.1016/j.ejps.2020.105233.
- [24] Y. Liu, R. M. C. So, and C. H. Zhang, “Modeling the bifurcating flow in an asymmetric human lung airway,” *Journal of Biomechanics*, vol. 36, no. 7, pp. 951–959, Jul. 2003, doi: 10.1016/S0021-9290(03)00064-2.
- [25] L. Puggelli, R. Furferi, and Y. Volpe, “Interactive mold design for paediatric lower airway manikin manufacturing: a feasibility study,” *Int J Interact Des Manuf*, vol. 18, no. 8, pp. 5801–5812, Oct. 2024, doi: 10.1007/s12008-023-01355-z.
- [26] A. D. Weatherall, M. D. Rogerson, M. R. Quayle, M. G. Cooper, P. G. McMenamin, and J. W. Adams, “A Novel 3-Dimensional Printing Fabrication Approach for the Production of Pediatric Airway Models,” *Anesthesia & Analgesia*, vol. 133, no. 5, pp. 1251–1259, Nov. 2020, doi: 10.1213/ane.0000000000005260.
- [27] B. Kuhn and I. Barjaktarevic, “Editorial: Understanding the Impact of Lung Ventilation Heterogeneity,” *Frontiers in Medical Technology*, vol. 6, Mar. 2024, doi: 10.3389/fmedt.2024.1332958.
- [28] Y. Liu, W. Qiu, L. Li, R. Chen, Y. Kang, and S. Ruan, “A Novel Approach to Pulmonary Bronchial Tree Model Construction and Performance Index Study,” *Frontiers in Pharmacology*, vol. 14, Nov. 2023, doi: 10.3389/fphar.2023.1254804.

[29] D. Kundu and M. V. Panchagnula, "Asymmetric Lung Increases Particle Filtration by Deposition," Scientific reports, vol. 13, no. 1, Jun. 2023, doi: 10.1038/s41598-023-36176-3.

[30] "6 Pack Rapid-Filling Self-Sealing Tropical Colored Water Balloons | Michaels." Accessed: Sep. 30, 2026. [Online]. Available: <https://www.michaels.com/product/6-pack-rapidfilling-selfsealing-tropical-colored-water-balloons-475092196973707270>

[31] Min, "What Are Water Balloons Made Of? | Materials, Myths & Safer Alternatives," Gadgets Feed. Accessed: Sep. 23, 2026. [Online]. Available: <https://gadgetsfeed.com/what-are-water-balloons-made-of/>

[32] Factory Direct Party, "Assorted Mini Latex Balloons - 5 In. | 50 Pack," Factory Direct Party. [Online]. Available: <https://factorydirectparty.com/products/round-latex-balloons-assorted-colours-5-in-50-pk-for-birthday-party-7>. [Accessed: Sep. 23, 2026].

[33] E. Robertson, "Different Types of Balloons: A Complete Guide to Materials, Shapes & Sizes," Balloons US. Accessed: Sep. 23, 2026. [Online]. Available: <https://balloons.online/blog/different-types-of-balloons/>

[34] "TransForm." Accessed: Sep. 24, 2026. [Online]. Available: <https://www.stryker.com/us/en/neurovascular/products/transform-occlusion-balloon-catheter.html>

[35] "Medical Balloons | Nordson MEDICAL." Accessed: Sep. 23, 2026. [Online]. Available: <https://interventional-solutions.nordsonmedical.com/Products/Catheter-Components/Medical-Balloons/>

[36] "Water Balloons : Bargain Balloons Canada." Accessed: Sep. 23, 2026. [Online]. Available: <https://support.bargainballoons.ca/support/solutions/articles/27000057303-water-balloons>

[37] E. Robertson, "Different Types of Balloons: A Complete Guide to Materials, Shapes & Sizes," Balloons US. Accessed: Sep. 23, 2026. [Online]. Available: <https://balloons.online/blog/different-types-of-balloons/>

[38] "Maximal Expiratory Flow - an overview | ScienceDirect Topics." Accessed: Sep. 24, 2026. [Online]. Available: <https://www.sciencedirect.com/topics/immunology-and-microbiology/maximal-expiratory-flow>

[39] Intravascular catheters — Sterile and single-use catheters — Part 4: Balloon dilatation catheters, ISO 10555-4:2023, 2023.

[40] "DeviceMD - TransForm Occlusion Balloon Catheter." Accessed: Sep. 24, 2026. [Online]. Available: <https://mydevicemd.com/medical-device/transform-occlusion-balloon-catheter>

[41] "Understanding Rubber Elasticity | PDF | Deformation (Mechanics) | Elasticity (Physics)." Accessed: Sep. 24, 2026. [Online]. Available: <https://www.scribd.com/document/406525881/Rubber-elasticity-pdf>

[42] "Foil vs Latex Balloons: Durability Comparison Chart," AIHUA Balloon. Accessed: Sep. 23, 2026. [Online]. Available: <https://aihuaballoon.com/balloon-durability/>

[43] "Compliant vs. Non-Compliant Balloon Catheters." Accessed: Sep. 23, 2026. [Online]. Available: <https://synergysurgical.com/blog/compliant-vs-non-compliant-balloons>

https://www.amazon.com/Assorted-Water-Balloon-Filler-Poly/dp/B08F3WBJ9V/ref=sr_1_11?channelId=520&clpRedir=Y&dib=eyJ2IjoiMSJ9.erT5wrdCmkTbqpkX5pMMCutVRemTQPi-kmL4ZvIwdk9hcPTGCL8Cm1jvi0OwyT56VCDvvdYqrev4yPCzsWc6ZLPxNNl5ntasRTQAjYADYG06CLDwV8aBu90RhEhnzSJPVdplNS0fsjMOoZBPO-d2twldwYXfzpWRcSe76Q8Y1DRV9Jg22T4bXR55koTebyz7hxZPMHfnCiPOLDIRxsZAPfwQJnNMwnqDJ-bMlsYwC4avTgJuGJvtV5JSmJ68T4ebzbCqRjrCd49Jx6tWFcGf_Tey6t-Ok3dhftLe9EjuRn4.07hM7VjtF9PyHOI-2tDBdmEa5AASF2AvNHYZiUBdYmU&dib_tag=se&keywords=water+balloons&plpRedirect=mhFallback&qid=1790207118&sr=8-11

https://www.amazon.com/Bezente-Assorted-Balloons-Birthday-Decorations/dp/B0BZCHMVTk/ref=sr_1_1?channellId=520&clpRedir=Y&dib=eyJ2J2Ijo1MSJ9.vwfcizDulfhCtDsAr-nYbPZvFk6B2to33uUhnemyHMWD6uxmT9uSBd3ZY2AlMYltjo2HUvCMMz0ns0_aXBzX-hOSFZH63gZxKTXLWmKOviwxEfznu1zeShrnpHrjRIHscdczHX5NxBmCnOFFTyNLqyMtUMeCnW-U7hbMu8TUESPIROwP0Ds9ubzVXi4xeSaA-xy77FUuMlxifOUphNIGECIIJ2P13ZOkgQS-CSA12GgS5VQAm760-P_TvZFBdlipm_V-O7accgz6_10zbVvBeBB81me2jGIzcli uLUhqxg.DwT1Ask6IEjxw9XJpvAEfygBzRKT10XZwuDjAmnlGDI&dib_tag=se&keywords=latex%2Bballoons&plpRedirect=mhFallback&qid=1790207152&sr=8-1&th=1

[47]“AccessGUIDID - DEVICE: TRANSFORM (07613327004700),” Nih.gov. Accessed: Sep. 24, 2026. [Online]. Available: https://accessguidid.nlm.nih.gov/devices/07613327004700?utm_source=gemini

[49] J. L. Allen, “Airway function throughout the lifespan: Pediatric origins of adult respiratory disease,” *Pediatr Investig*, vol. 3, no. 4, pp. 236–244, Dec. 2019, doi: 10.1002/ped4.12165.

[51] U.S. Department of Labor, Occupational Safety and Health Administration (OSHA). “1910.243 - Guarding of portable powered tools. | Occupational Safety and Health Administration.” Accessed: Sep. 16, 2026. [Online]. Available: <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.243>

Appendix A: Product Design Specification

Function

Flow limitation is the phenomenon in which increasing respiratory effort no longer increases airflow beyond a certain point during forced exhalation, because the airway itself becomes the limiting factor rather than muscles driving expiration [1, 2]. During forced expiration, intrathoracic pressure rises sharply and can exceed the pressure inside the airway, resulting in the airway walls, specifically the bronchi, to narrow and eventually reach a choke point past which further effort in exhalation cannot increase flow [3]. This mechanism is central to interpreting spirometry, since flow-volume curves reflect the mechanical properties of airways rather than respiratory muscle effort alone [4, 5]. It is most relevant to obstructive diseases such as asthma, cystic fibrosis, and COPD, where airway walls are more prone to premature collapse or are already narrowed by inflammation, mucus, or loss of elastic recoil. This leads to prominent flow limitation occurring during forced exhalation [6]. This device will model the branching anatomy of the airway and use flexible materials to replicate the compression and collapse that occurs in the affected patient population. This will allow the users to visualize the equal pressure point (EPP) and the resulting choke point as it moves distally through the airway. The device is intended to physically demonstrate flow limitation during forced expiration for use in an educational teaching video. The final video will be used to teach medical fellows and students how these airway mechanics underlie clinical measures such as spirometry, and how they explain and monitor these obstructive conditions that experience flow limitation.

Client requirements

- The device must demonstrate flow limitation during forced expiration by visibly showing the choke point and EPP and the compression travelling distally through the airway, from the lower trachea, through a few generations of branching, and downstream towards the alveoli.
- The final device must be 3D-printed, stay permanently in ECB, and only needs to support a pre-recorded video, spanning 6 to 10 seconds, for teaching fellows and medical students about flow limitation.
- The airway model must mimic a simplified model of the branching anatomy observed in lungs. A multi-compartmental design is preferred, ideally a four-compartment model, but a minimum of two compartments is required.
- The material used to make the branches of the airway model must be thinner and more flexible than last year's model, so that choke point can shift asymmetrically across the generations of branches.
- The box that housed last year's model should be reused, unless the box proves to be insufficient.
- The team must stay under a budget of \$1000.

Design requirements

1. **Physical and Operational Characteristics**
 - a. *Performance requirements*

- i.* The device must visually demonstrate flow limitation in an airway model and the movement of the choke point throughout the airways as forced expiration occurs. The movement of the choke point towards the alveoli must be visible enough to be seen on a 6 to 10 second video for demonstration purposes. The model must also accurately model human airways with at least two but ideally four chambers (1 or 2 generations of bifurcation) with adequate elasticity to return to an uncompressed state when pressure is removed, allowing the demonstration to be re-ran a minimum of 100 times without losing elasticity in the model airways. The device must be able to contain pressures of at least 2.3 kPa above atmospheric pressure with no leakages to accurately represent conditions in the human anatomy surrounding the airways [7]. These conditions in the human airways are not consistent from person to person, especially in patients with obstructive airway diseases; airways in patients with COPD have increased compliance (stiffness) compared to healthy lungs, while airways in patients with asthma have thickened walls due to excess mucus [8]. The device should have a level of adjustability in airway stiffnesses, applied pressures, and lengths to reflect how different disease states and loading conditions affect the movement of the choke point during forced expiration.
- b. Safety*
 - i.* As part of its regular function, the device will be connected to compressed air via a hose. Use of pneumatic-powered tools and hoses are regulated according to OSHA standard 1910.243(b) [9], which requires a tool retainer to prevent accidental ejection of the hose and that the hose and hose connections be designed to withstand the pressure demands without failure. The device itself must also be rated to maintain normal operational pressures with no risk of explosion. The materials used in the device, especially those accessible to users, should be non-toxic, and the device itself should have limited sharp edges and pinch points.
- c. Accuracy and Reliability*
 - i.* The most important component that the device must accurately model is the visible formation and movement of the choke point upstream two generations during forced expiration [10]. The device should also model true human airway transmural pressures of 2.3 kPa and average compliance of 0.225 l/cmH₂O with variance along the airway as closely as possible [7, 11]. However, the focus should be on modeling accurate choke point behavior. This choke point movement must be visibly demonstrated with no mechanical failures or major changes in pressure values for a minimum of 100 simulated runs of forced expiration.
- d. Life in Service*
 - i.* The success of the device will be evaluated based on the criterion that the model is able to produce visibly discernable choke points along the airway, closer to the alveoli, during forced expiration. This event should have a sufficient time constant, around 6 to 10 seconds per the client's request, for quality interpretation by the students who will watch the video. The device should be capable of completing a minimum of a 100 simulation cycles across testing, operation, and the final video recording without degradation of mechanical performance or loss of the flow limitation effect.

e. Shelf Life

- i.* Although the device will not be reused after the completion of the video, any components with a defined shelf life shall be stored per their manufacturer specifications, and will remain within their rated shelf life up to the date of the final video recording. Prior to use for the final video recording, the device will be stored at standard room conditions (20-22°C, ambient humidity) in room 1070 at Engineering Centers Building.

f. Operating Environment

- i.* Beyond the controlled temperature (20-22°C) and pressure (1 atm) of the testing environment, the device is not expected to be exposed to significant humidity variation, dust, corrosive fluids, or vibrations outside normal laboratory benchtop conditions. The device will be operated and tested exclusively by the undergraduate students on team “Flow State”. There are no unforeseen hazards or exposure to outdoor elements, insects, or high-shock loading given the controlled indoor lab setting.

g. Ergonomics

- i.* The device should be easy to move and transport as needed for any testing needed with the team. The device should not need to be moved often or at all after all testing and fabrication is done since the client is looking for the team to demonstrate how the device works via video. In addition, the model should be easy to properly use and demonstrate the choke points. Applying force and pressure via a compressed air hose should only require one hand to prevent any strain while also being able to operate and model the specific flow limitations and pressure points.

h. Size

- i.* The physical model will be able to sit on a lab bench and be large enough to see visibly in the video representation. The pressure chamber from the previous design will remain the same dimensions around $20 \times 20 \times 20$ cm with acrylic thickness of 20 mm [17]. This is equipped with pressure taps for measuring box pressure, upstream/airway pressure and downstream pressure. The main airway tubing should be from 15 mm to 18 mm to stimulate the correct adult airway geometry. The flexible section should have a very small thickness of 0.5 mm to 1.0 mm in order to properly demonstrate the airway model [12].

i. Weight

- i.* The maximum load constant (LC) is set at 23 kg to ensure safety when transporting these objects [13]. The acrylic chamber weighs 12 kg, well within the limit of safety for the object [17]. The lung model inside the chamber will weigh no more than 0.454 kg as it will be created with flexible materials ensuring that using the model is as effortless as possible.

j. Materials

- i.* The material used to model the airway must be sufficiently flexible to show visible compression at the location of the choke points. Ideally, the material will match the biological properties of the airway walls as closely as possible, including a Young’s modulus of 0.17 - 0.65 MPa [14] and a Poisson’s ratio of 0.41 - 0.45 [15]. Additionally, the material must exhibit a gradient in compliance (dA/dP_{tm}) to ensure the choke point travels distally [16]. This gradient will be accomplished by varying the material

thickness, meaning that the material chosen must be viable at a wide range of thicknesses. The alveoli must be modeled using a thin, balloon-like material that is able to expand as the model takes in air, and this material must be conducive to a tight, leak-proof seal with the airway model. The vacuum chamber to be used is fully transparent and is composed of pressure-resistant acrylic with a thickness of 20 mm [17]. This material will resist deformation and leakage, and allow for complete visualization of the airway model throughout testing.

k. Aesthetics, Appearance, and Finish

- i. The final product must clearly display the full length of the airway model so that the distally moving choke points are visible throughout the respiratory cycle. The product must replicate the airway in an intuitive manner such that students understand how the anatomy of the model correlates with human anatomy, and labels should be included to indicate key anatomical features for added clarity. Most students will access the model through a video demonstration, so the product must be conducive to video recording.

2. Production Characteristics

a. Quantity

- i. Per client requirements, one prototype is required. In order to allow for widespread viewing of the model, a video displaying the key features of the model will also be provided to the client.

b. Target Product Cost

- i. The vacuum chamber from the previous project, which cost \$466.83 [17] and has already been covered by the past client budget, will be reused. The total additional cost of the airway model materials to be used in this iteration is estimated to remain under \$150. The client has provided a total budget of \$1000 for this semester, which is well beyond the estimated semester project cost.

3. Miscellaneous

a. Standards and Specifications

- i. The model will operate using compressed air for testing and the final video demonstration. All operators of the model, and surrounding observers, must wear adequate eye protection in the front and side of the eyes to protect from potential flying debris [18]. Air receivers on the device should be equipped with an indicated pressure gauge to safely observe the pressure delivered to the device [19]. Safety valves, indicating, and controlling devices should be installed and located so they cannot be readily rendered inoperable [19].

b. Customer

- i. The client, Dr. Chris Green, is professor emeritus in the Division of Pulmonology and Sleep Medicine at the University of Wisconsin - Madison. Dr. Green has requested a device that accurately models Flow Limitation for instruction of medical students. The model will result in a final video that should show an understandable depiction of the device. This will be achieved by slowing down the demonstration to show the movement of choke points and depicting multiple cycles. The model should have at least two

chambers with four chambers being the most preferable to show the distal movement of choke points.

c. Patient-related concerns

The client requests a short video demonstrating the model in use to be used in classrooms. Because of this, there is no posed risk to the client or patient. With this in mind, there will only be an emphasis on keeping the operator safe. First is biosafety and toxicity. The materials used to print the 3D model of the airways should be constructed of materials that are nontoxic and non-degassing under pressure to prevent chemical inhalation by the user. Another concern is pressure and shattering. The pressurized chamber should be able to withstand significantly more pressure than the model inside will need to be pressurized to. Brittle materials such as glass should not be used. Lastly is sterilization and maintenance. All surfaces and materials should be able to be disinfected and cleaned with standard disinfection without degradation or ruin.

d. Competition

Existing market and research solutions only provide computational statistics based on computer generated models or static anatomic models, leaving a gap between a physical model that can visualize pressure and chokepoints. The first model of competition was created by the department of Mechanical Engineering at Yamaguchi University created models of the airways by developing a computational fluid dynamics (CFD) that reconstructs a patient's airways directly from CT scan data. The drawback of this model is it does not include an exterior pressure system and pressure drops and changes or chokepoints [20]. The second model is called the Polak and Yutchen Computation Model. This mathematical model demonstrates wave speed flow limitation and choke point formation across the bronchial tree during forced expiration. This model takes place solely in a computer model called *silico*, removing the opportunity to see a 3D model. The physical demonstration provides a visual representation of a pressured chamber and moving choke points [21].

References

- [1] C. Tantucci, “Expiratory Flow Limitation Definition, Mechanisms, Methods, and Significance,” *Pulm Med*, vol. 2013, p. 749860, 2013, doi: 10.1155/2013/749860.
- [2] T. C and G. V, “Flow limitation: an overview,” PubMed, Accessed: Sep. 15, 2026. [Online]. Available: <https://pubmed.ncbi.nlm.nih.gov/10546481/>
- [3] Z. Ms, “The physiology of forced expiration,” PubMed, Accessed: Sep. 15, 2026. [Online]. Available: <https://pubmed.ncbi.nlm.nih.gov/16263442/>
- [4] “Lung Flow Volume Curve - an overview | ScienceDirect Topics.” Accessed: Sep. 15, 2026. [Online]. Available: <https://www.sciencedirect.com/topics/biochemistry-genetics-and-molecular-biology/lung-flow-volume-curve>
- [5] “Pulmonary Function Testing - PMC.” Accessed: Sep. 15, 2026. [Online]. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC7158317/>
- [6] R. L. Dellacà et al., “Detection of expiratory flow limitation in COPD using the forced oscillation technique,” Feb. 2004, Accessed: Sep. 15, 2026. [Online]. Available: <https://publications.ersnet.org/content/erj/23/2/232>
- [7] K. L. Steimle, M. L. Mogensen, D. S. Karbing, J. Bernardino de la Serna, and S. Andreassen, “A model of ventilation of the healthy human lung,” *Computer Methods and Programs in Biomedicine*, vol. 101, no. 2, pp. 144–155, Feb. 2011, doi: [10.1016/j.cmpb.2010.06.017](https://doi.org/10.1016/j.cmpb.2010.06.017).
- [8] C. M. Ionescu, P. Segers, and R. De Keyser, “Mechanical Properties of the Respiratory System Derived From Morphologic Insight,” *IEEE Transactions on Biomedical Engineering*, vol. 56, no. 4, pp. 949–959, Apr. 2009, doi: [10.1109/TBME.2008.2007807](https://doi.org/10.1109/TBME.2008.2007807).
- [9] U.S. Department of Labor, Occupational Safety and Health Administration (OSHA). “1910.243 - Guarding of portable powered tools. | Occupational Safety and Health Administration.” Accessed: Sep. 16, 2026. [Online]. Available: <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.243>
- [10] O. F. Pedersen and J. P. Butler, “Expiratory Flow Limitation,” *Comprehensive Physiology*, vol. 1, no. 4, pp. 1861–1882, 2011, doi: [10.1002/j.2040-4603.2011.tb00374.x](https://doi.org/10.1002/j.2040-4603.2011.tb00374.x).
- [11] J. Mead and J. L. Whittenberger, “Physical Properties of Human Lungs Measured During Spontaneous Respiration,” *Journal of Applied Physiology*, vol. 5, no. 12, pp. 779–796, Jun. 1953, doi: [10.1152/jappl.1953.5.12.779](https://doi.org/10.1152/jappl.1953.5.12.779).
- [12] S. David, J. Goldin, and C. W. Edwards, “Forced Expiratory Volume,” in *StatPearls, Treasure Island (FL): StatPearls Publishing*, 2026. Accessed: Sep. 17, 2026. [Online]. Available: <http://www.ncbi.nlm.nih.gov/books/NBK540970/>

- [13] CDC, “Revised NIOSH Lifting Equation,” *Ergonomics and Musculoskeletal Disorders*. Accessed: Sep. 16, 2026. [Online]. Available: <https://www.cdc.gov/niosh/ergonomics/about/RNLE.html>
- [14] “Dynamic Properties of Human Bronchial Airway Tissues,” ResearchGate. Accessed: Sep. 15, 2026. [Online]. Available: https://www.researchgate.net/publication/51958959_Dynamic_Properties_of_Human_Bronchial_Airway_Tissues
- [15] S. J. Lai-Fook and R. E. Hyatt, “Effects of age on elastic moduli of human lungs,” *J Appl Physiol* (1985), vol. 89, no. 1, pp. 163–168, Jul. 2000, doi: 10.1152/jappl.2000.89.1.163.
- [16] T. Miyazawa, S. Nobuyama, H. Nishine, H. Handa, and M. Mineshita, “Choke point physiology in airway stenting: A case presentation and discussion,” *Respiratory Investigation*, vol. 54, no. 4, pp. 237–240, Jul. 2016, doi: 10.1016/j.resinv.2016.02.006.
- [17] “Vacuum Degassing Chamber, Clear Degassing Chamber Kit with Pressure Gauge, Two Way Valve, High Transparency Acrylic, Fast Ventilation, Airtight Seal : Amazon.it: Industrial & Scientific.” Accessed: Sep. 15, 2026. [Online]. Available: <https://www.amazon.it/degassamento-sottovuoto-trasparente-trasparenza-ventilazione/dp/B0G6Z5DF3K>
- [18] “1926.102 - Eye and face protection. | Occupational Safety and Health Administration.” Accessed: Sep. 14, 2026. [Online]. Available: <https://www.osha.gov/laws-regs/regulations/standardnumber/1926/1926.102>
- [19] “1910.169 - Air receivers. | Occupational Safety and Health Administration.” Accessed: Sep. 14, 2026. [Online]. Available: <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.169>
- [20] F. Jiang, T. Hirano, C. Liang, G. Zhang, K. Matsunaga, and X. Chen, “Multi-scale simulations of pulmonary airflow based on a coupled 3D-1D-0D model,” *Computers in Biology and Medicine*, vol. 171, p. 108150, Mar. 2024, doi: 10.1016/j.combiomed.2024.108150.
- [21] “Computational Model for Forced Expiration from Asymmetric Normal Lungs | Annals of Biomedical Engineering | Springer Nature Link.” Accessed: Sep. 16, 2026. [Online]. Available: <https://link.springer.com/article/10.1114/1.1588651>

Appendix B: Airway Fabrication Protocol

Materials:

- Formlabs Flexible 50A Resin
- FormLabs Form 4 printer at the Wendt Design Innovation Lab
- Isopropyl alcohol wash station
- UV post-cure unit
- Small latex water balloons
- Cyanoacrylate (super glue)

Procedure

1. Construct the four-compartment branching airway in SolidWorks, extending from the lower trachea through 2 generations.
2. Export the model as an .stl file and import into PreForm slicer software. Orient the part to minimize support contact with internal lumens, and generate supports.
3. Print the model on the Form 4 printer using Flexible 50A Resin at a layer thickness of 0.1 mm.
4. Once printing is finished, remove the airway from the build plate and wash in isopropyl alcohol for 20 minutes to remove uncured resin.
5. After the first wash, allow the airway to dry completely.
6. If the material is still sticky to the touch, repeat steps 4 and 5.
7. Once the material is no longer sticky to the touch, remove any remaining supports.
8. Place the airway in a beaker of water for 2 minutes.
9. Cure the fabricated airway using UV light for 7 minutes at 70°C.
10. Adhere four water balloons to the airway's four distal ends using cyanoacrylate, and allow it to cure for 15 minutes.

Appendix C: Expense Table

Item	Description	Manufacturer	Mft Pt#	Vendor	Vendor Cat#	Date	QTY	Cost Each	Total	Link
Airway Materials										
FormLabs Flexible 50A Resin	Elastic resin used to print on FormLabs SLA printers.	FormLabs	N/A	DI Lab	N/A	TBD	TBD	\$0.29/g	TBD	Link
Assorted Water Balloon	Multi-color latex 3" water balloons 100ct	Arcady	N/A	Amazon	N/A	TBD	1	\$4.94	\$4.94	Link
Loctite Super Glue Ultra Gel Control	Tough silicone gel super glue	Loctite	N/A	Amazon	N/A	TBD	1	\$4.49	\$4.49	Link
Misc.										
BMP388 Precision Barometric Pressure and Altimeter	Pressure sensor, accurate up to 8 Pascals	N/A	N/A	Amazon	N/A	TBD	1	\$16.99	\$16.99	Link
STEMMA QT / Qwiic JST SH 4 pin to premium male headers cable	Connector from QT to Male Headers for Arduino	N/A	N/A	Amazon	N/A	TBD	1	\$6.70	\$6.70	Link
								TOTAL:	\$33.12	