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Kidney and Lung Demonstrations to Introduce Engineering Concepts to Middle School Students and Their Grandparents

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Abstract

The authors have developed a series of hands-on activities and demonstrations themed around the organs of kidneys and lungs to introduce engineering concepts in a summer camp for 4th-8th graders and their grandparents. The examples are motivated from the faculty members' research labs, which emphasize understanding and treating kidney and lung damage. The kidney activities focus on the chemical engineering concept of separation via filtration, and the lung activities center around transport and fluid mechanics. This paper details the physical games, custom 3D printed models, and activities developed around kits available for purchase that the authors have deployed in the summer camp along with some discussion guides on the topics and on the engineering design principles underlying artificial kidneys and aerosol medications targeted to regions of the lungs.

Introduction

The Oklahoma State University Alumni Association has hosted Grandparent University as an annual 3-day residential summer camp offered as two sessions each summer since 2003, except in 2020 due to the COVID-19 pandemic. Grandparent University is for children ages 7 to 13 who have a parent or grandparent who is an active member of the Alumni Association and are accompanied by their grandparent(s) or adult chaperone of their grandparents' generation. The camp is intended to be a fun-filled experience that actively engages kids in academics on campus while creating memories for grandchildren and their grandparents. The children and grandparent groups enroll in one of the "majors" offered and complete six hours of activities in that major during the camp. The classroom activities are led by university faculty, staff, and students. The authors have developed and hosted a camp session called the "biomedical engineering (BME) major" at the annual Grandparent University targeting 4^{th}-8^{th} graders and their grandparents.

Some similar camps for children and their grandparents have been described in the ASEE conference proceedings literature[1-3], primarily with descriptions of the activities. Here, we aim to make a comparable contribution featuring the lessons we developed or repurposed. Other activities have been developed to introduce chemical engineering principles to undergraduate students using topics from the physiological function and/or disease treatment of the lungs[4-7] and kidneys[7-14]. However, the authors are unaware of a related set of lessons targeted to middle school students or adult lay audiences outside of the present work. The goal of this paper is share the lessons and notes on their implementation, not to conduct a research study on the camp participants.

In addition to sharing the specific activities listed here for direct use in outreach events, we share these as examples of creating or adapting activities both to communicate concepts from our field and to connect to our research areas. We incorporated undergraduate and graduate students from our labs as collaborators and teaching assistants alongside the faculty authors for developing and delivering the educational activities described here. Thus, this paper exemplifies the integration of teaching, research, and community engagement.

This paper is organized as follows. First, connections to chemical engineering are articulated. Then the main body of the paper details the instructional activities grouped into kidney activities and lung activities. At the end of this paper, we describe some of our experiences in teaching and refining the activities, feedback from participants, and how these efforts promote STEM. Finally, two appendices are provided. Appendix A lists the learning objectives for the camp session that are intended to be shared with participants. Appendix B gives a simple description of background concepts involved in the lesson, which is intended for instructors unfamiliar with the applications.

Connections to Chemical Engineering

The authors are chemical engineering faculty and interdisciplinary students in the research labs of those faculty. While the activities for the BME major at Grandparent University are themed around two major organs in the human body, the authors designed the activities to emphasize separation process principles and transport phenomena—two key areas of the chemical engineering curriculum. The kidney activities focus on filtration involving both adsorption to surfaces and pore and particle size-based mass transfer differences. The lung activities introduce fluid mechanics in the lung airways and particle motion in the fluids of the lung (air, vapor droplets, and mucus). Concepts including inertia, diffusivity, Brownian motion, and others are incorporated. The design principles emphasized in the lessons are quite general across engineering disciplines. To distinguish these activities as chemical engineering exercises particularly in institutions that have separate chemical engineering and bioengineering/biomedical engineering departments, the lessons could be labeled with an alternative title such as “Chemical Engineering Processes in the Human Body”.

Instructional Activities

Overview

The chemical engineering concepts of filtration and fluid dynamics are introduced by application to blood filtration in the kidney and air and particle movement in the lungs. The activities explore the engineering design principles behind artificial kidneys and aerosol medications targeted to regions in the lungs. The activities described below are grouped into kidney activities and lung activities, which are each about three hours long.

Kidney Activities

To teach how healthy and diseased kidneys work differently and how to engineer treatments, the first three-hour session (Day 1) involves the following activities: (1) conducting water filtration experiments and discussing background on filtration and kidneys as filters, (2) playing a game where participants pretend to move through filters, (3) simulating kidney filtration with a physical model augmented by 3D printed filters for healthy and diseased cases and a 3D printed model of a glomerulus, and (4) discussing engineering design principles for replacing the kidneys with artificial filters. All activities serve to emphasize the importance of filtration.

Kidney Activity 1: Water Filtration Experiments

After introducing filtration and the kidneys using the recommended video resource "What are Kidneys?"[15], conduct two experiments demonstrating mechanical and chemical filtration[16]. Briefly, both experiments involve using water or pop bottles cut in half, and the top half is inverted into the bottom half. The top holds the filtration materials, and the bottom collects the filtrate (Figure 1a). In the mechanical filtration experiment, cotton is the porous material that removes solid particulates like cornmeal stirred into colored water. In the chemical filtration experiment, activated carbon or the content of a Brita filter cartridge are used to remove food coloring from water. Instruct the participants to work together to build the filters and conduct the experiments to test the performance of different types of filtration materials (Figure 1b).

Kidney Activity 2: Pore Motion Activity

This activity is a physical game where participants pretend to be small molecules moving through the kidney filters by hopping or waking through paths marked on the floor[16] (Figure 1c). Mark paths of different widths on the floor to illustrate varying pore widths. The feet of each participant represent molecules or particles of different sizes moving through the pores. The hopping motion is encouraged for kids to expend energy but also to represent the motion of energetic molecules. Participants are encouraged to avoid moving outside the boundaries of the paths. One path should be outlined in double-sided tape to simulate adsorption to the surface inside pores due to "sticky" interactions, independent of particle size. Having all participants hop through the sticky path last gives an element of surprise. Connect the non-sticky paths to the mechanical filtration experiment, and discuss the chemical filtration concepts demonstrated by the sticky path and the related experiment.

Figure 1: Filtration experiments and physical activity adapted from our prior work[16].
(a) Mechanical filtration experiment to separate cornmeal from colored water. (b) A grandparent and a grandchild conducting the experiment as a team. (c) Children hopping on one foot through pathways marked on the floor with tape during the pore motion activity.

Kidney Activity 3: Kidney Filtration Physical Model Experiment

Carolina Biological Supply sells a product called the Kidney Filtration Simulation Kit[17], which includes the components for 15 kidney filtration physical models (Table 1). The educational materials packaged in the kit focus on the physiological processes inside nephrons of the kidneys: filtration (in the glomerulus) and reabsorption (in the tubule). We adapted the lesson in two substantial ways; the adapted experiment is detailed after this paragraph. First, we wanted to emphase the role of the pores in filtration and how the pores get damaged in disease, so we designed custom 3D printed filters to replace the plastic mesh included in the kit (Figure 2). The filters fit the tubes that represent the inlet and outlet capillaries. Filters for two cases were designed: healthy and diseased. In the healthy case, only the small beads should pass through the pores of the filter. In the diseased case, the triple-pointed tri-beads that represent proteins should also fit through the larger triangular pores. The bead and pore shapes are not realistic, but beads represent the biologically accurate corresponding molecules that pass or do not pass through the healthy and/or diseased filters. Additionally, we included a plate or a bowl to the list of components to help with collecting beads after they pass through our custom filters. The second modification to the lesson was motivated by the fact that the filters used in the kidney filtration physical model look very different than an anatomical glomerulus. We used SOLIDWORKS to design a 3D anatomical model of a glomerulus to illustrate the bundle of capillaries (Figure 3). The 3D model of a glomerulus capsule and capillary bundles follows current literature describing the size and volume of an average human glomerulus, which is approximately 200 micrometers in diameter, and considers both artistic renderings and microscopy images currently available to scale the view inside the glomerulus to 5 inches. The back is flattened to allow the model to lie flat on a surface. Anatomically, the outer shell should extend around the capillaries as a spherical capsule, but we chose to leave it open to highlight the capillaries. Standard 3D printers and splicing software were used to print each physical model. All the files for 3D printed models used in the kidney and lung activities are available upon request to the first and last authors, respectively.

For the experiment, first assemble a kidney filtration physical model for each group using the components listed in Table 1 and shown in Figure 2a and Figure 2b. In this experiment, participants compare the performance of multiple filters for screening beads of different sizes to demonstrate how blood components are filtered by a kidney nephron and its bundle of capillaries called the glomerulus.

The activity begins with all the beads in the cylinder marked “renal artery,” representing the capillary inlet. The participants must use two hands to hold and tilt the model or have the help of another individual to hold the two cylinders for the “renal artery” and “renal vein” snug against the 3D printed filter (Figure 2b). Shift the “renal artery” upward and allow the beads to move down and to the right through the model toward the “renal vein,” representing the capillary outlet (Figure 2c). The small beads representing filtrates—glucose, amino acids, urea, and salt—should fall through the pores of the 3D printed filter, while the larger beads representing the retentates—red blood cells, white blood cells, and proteins—stay in the “renal vein” cylinder (Figure 2c). The nephron cup catches the filtrate. A plate or bowl underneath helps to catch supplies that miss the cup and prevent the distraction of searching for the fallen beads. While anatomically the filtrate would filter through the glomerulus and exit out in one pass, this activity often requires multiple tilts of the setup to completely filter out all the small beads. In addition to the 3D

printed filter for the healthy case shown in Figure 2b, c, and e, other filters should be explored including the original plastic mesh (Figure 2d) similar to that found in packaging for supermarket produce, the 3D printed filter for the diseased case (Figure 2f), or even a simple hole-punched piece of paper taped together, if previous options are not easily obtainable. In this physical model, each one of the supplies represents a specific biological substance or anatomical feature (Table 1 and Figure 2g). The beads represent the cells and molecules in the blood. The illustration in Figure 2g shows which species should end up in the filtrate and in the capillary outlet for the healthy case. In the diseased conditions, the proteins (tri-beads) should also pass through the diseased filter. Youtube videos[18] on the topic of diabetic nephropathy describe the presence of protein in the urine of patients after the glomerular filter is damaged by diabetes.

Table 1: Supplies for one kidney filtration physical model.

Components	**Biological Entity Represented**
4 Large Red Beads	Red Blood Cells
4 Large White Beads	White Blood Cells
4 Large Purple Tri Beads	Protein Molecules
20 Small Green Beads	Glucose Molecules
20 Small Purple Beads	Amino Acid Molecules
20 Small Yellow Beads	Urea Molecules
20 Small White Beads	Salt Ions
1 Small Plastic Cup with Lid	Nephron
2 Plastic Cylinders 1-inch in Diameter and Open on One End	Inlet and Outlet Capillaries
3D Printed Filters (not in the kit) or Plastic Mesh	Glomerulus or “kidney filter”
1 Plate or Bowl (not in the kit)	None

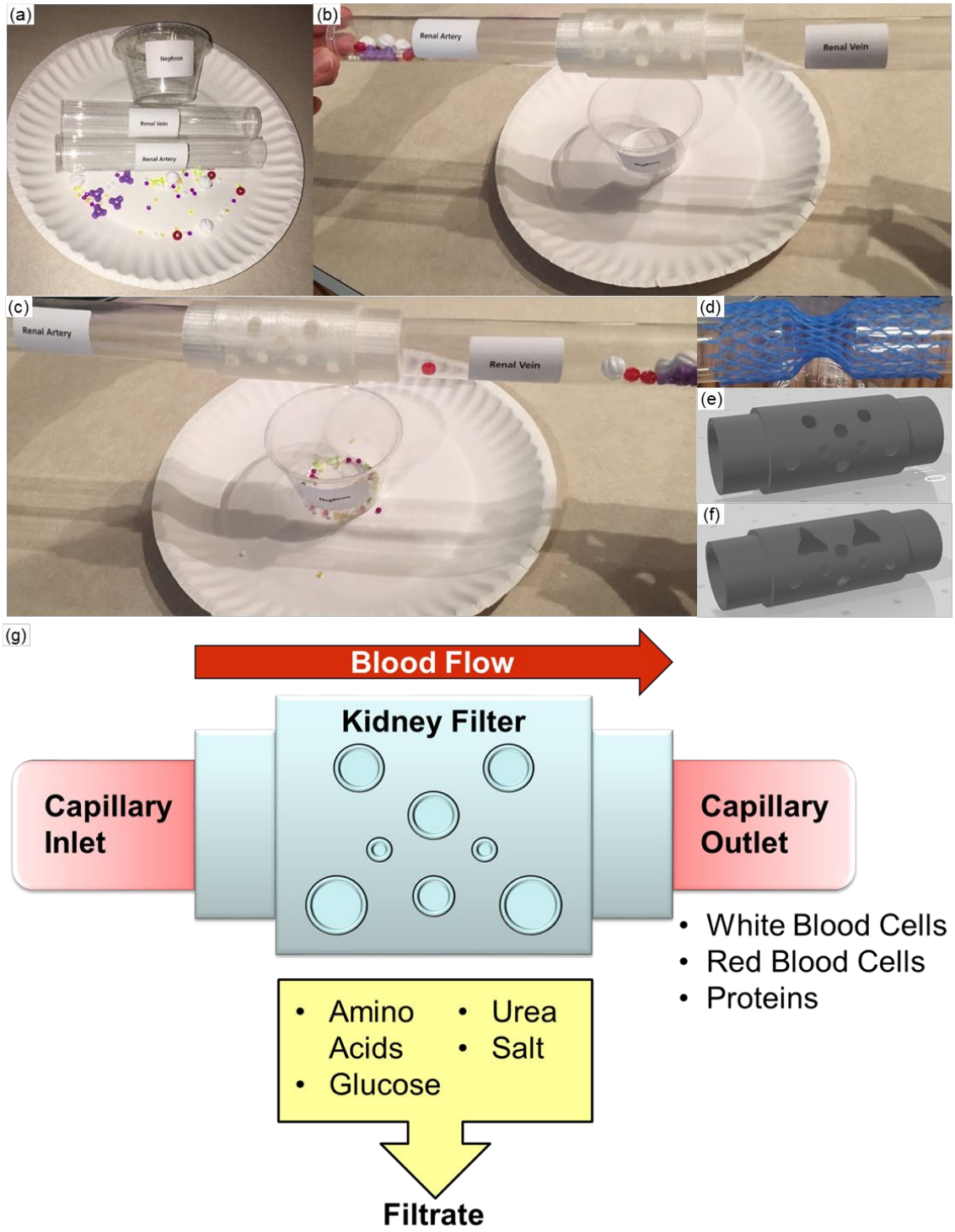

Figure 2: Kidney filtration physical model. (a) Components of one kidney filtration physical model from a kit purchased from Carolina Biological Supply[17]. Model set up with our custom 3D printed filter: (b) before filtration and (c) after filtration. Filter options: (d) plastic mesh included in the kit or 3D printed filters for (e) "healthy" case and (f) "diseased" case (SOLIDWORKS renderings shown). (g) Illustrated explanation of the biological interpretation of the kidney filtration physical model in the healthy case.

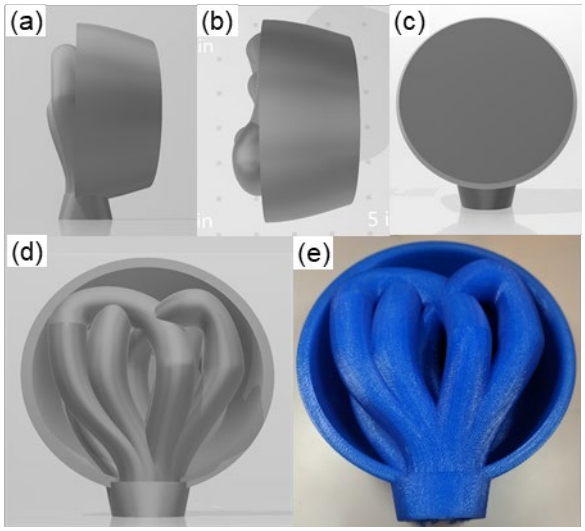

Figure 3: 3D printed glomerulus. (a) Left, (b) top, (c) back, and (d) front views rendered in SOLIDWORKS. (e) Printed 3D model with height and width of 5 in.

Kidney Activity 4: Discussion of Engineering of Artificial Kidneys

The diseased filter case from the previous activity leads directly into a discussion of approaches for treating kidney diseases. Specifically, we encourage a discussion of technological advancements featuring membrane filtration devices to supplement or replace kidney function. The discussion typically follows the structure of introducing a technology with a video, brainstorming advantages and disadvantages as a large group, and then suggesting the next innovation on the horizon to address some of the disadvantages. The outline (recommended videos listed as citations) is (1) dialysis to filter the blood with an external machine that patients have to travel to at a facility[19-21], (2) external artificial kidney that is worn by a patient[22, 23], and (3) internal artificial kidney implanted in a patient[24-26]. Kidney transplantation can also be discussed as an alternative.

Lung Activities

To teach how healthy and diseased lungs work differently and how to effectively treat lung diseases and improve pulmonary healthcare using computer-aided design and engineering, the second three-hour session (Day 2), i.e., "LUNGevity session" promotes the concept of "*in silico* pulmonary healthcare" and involves the following activities: (1) using augmented reality t-shirt to visualize and learn the physiological structures of the lung and other organs, (2) building balloon lung models with different elasticities to learn how the breathing capabilities can be damaged by lung diseases, (3) bowling using balls with different volumes and densities to learn the key factors that can influence the targeted delivery efficiency to the designated lung sites, and (4) exhibiting how pulmonary air-particle flow simulations help engineers and physicians to optimize the inhalation therapy plans for patients with lung diseases. All activities serve the four focuses of the LUNGevity session: structure, function, disease, and treatment. We also describe two newly designed hands-on modules that will be piloted in the next offering of Grandparent University.

Lung Activity 1: "X-ray" Test of Lung Structure Using Virtuali-Tee®

First, introduce the anatomical features of the human respiratory system using the visualization of 3D human respiratory systems (Figure 4a) and the physical 3D printed airways models (Figure 4b). Ask students to volunteer and draw human respiratory systems on the whiteboard. Have the students explain the key anatomical features of the human respiratory systems that they can show from their drawings (Figure 4c). Working in groups, give students the opportunity to check the physiological 3D airway structures and the connections between the lung and other organs in the augmented reality (AR) human body, using a uniquely designed T-shirt (Virtuali-Tee product sold by Curiscope) accompanied by the commercialized cell phone app[27]. By pointing a cell phone camera towards different locations on the T-shirt, students can view the virtual 3D anatomical structures inside the human body, including the human respiratory system (Figure 4d). While most young students may not have their own smart phone, the adult chaperones usually have smart phones. It is recommended that staff assist with downloading the app if needed and that extra devices be available for participants.

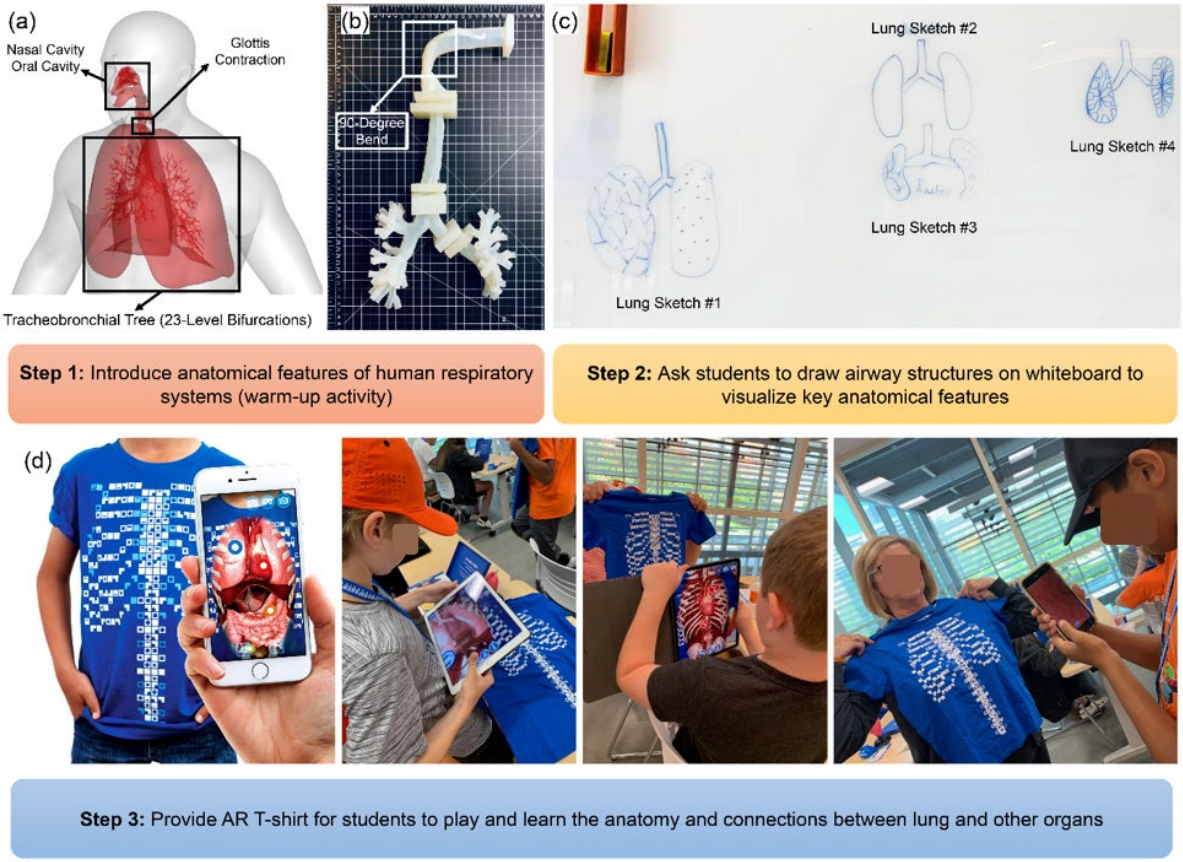

Figure 4: Lung Activity 1 "X-ray" test of lung structure using augmented reality (AR) T-shirt and cell-phone app. (a) Virtual lung model, (b) 3D printed human respiratory system replica, (c) sketches of human lungs drawn by students, and (d) AR T-shirt and lung tissue visualization using a cell phone app.

Lung Activity 2: Balloon Lung Demonstration of Pulmonary Functions and Disease

Use the balloon lung model[28-30] (Figure 5) to explain the lung (pulmonary) function and the underlying flow dynamics of inhalation and exhalation. The following points should be made in explanation based on the student observations by playing with the balloon lung model.

(1) The movement of the diaphragm (i.e., the yellow membrane with handle in the balloon lung model) led by the external intercostal muscle motions are the driving force to expand and contract the lungs (i.e., the two balloons).

(2) During the expansion and contraction of the lung, the lung volume change creates pressure differences to draw air in and out of the lung.

(3) Introduce the lung structure and function changes caused by multiple obstructive and restrictive diseases, which lead to breathing difficulty. Specifically, restrictive lung diseases prevent the lungs from fully expanding with air. Obstructive lung diseases lead to airway wall inflammation and extra secretion of mucus, which lead to the blockage of the airways.

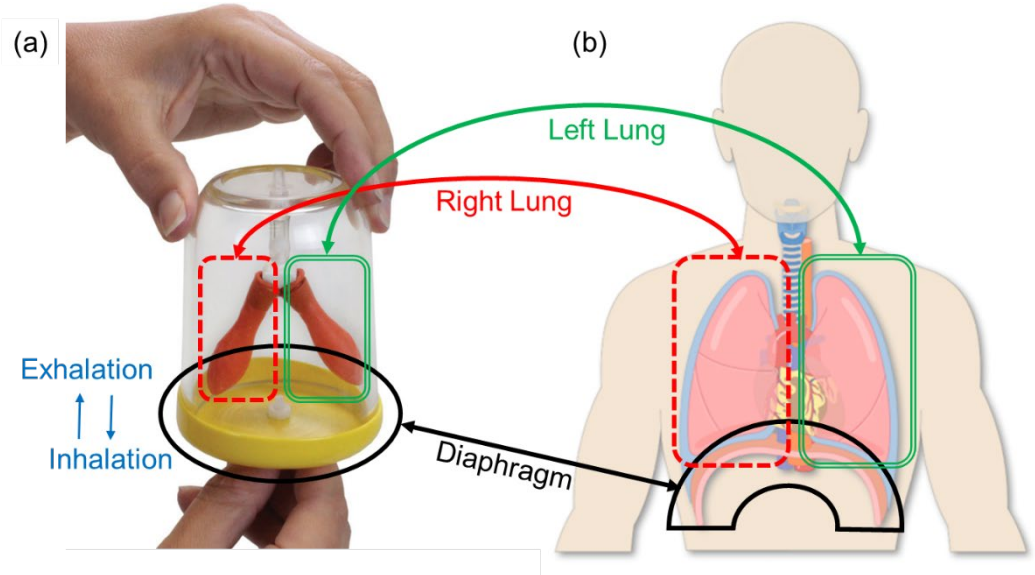

Figure 5: Hands-on benchtop experiment for studying the disease-specific pulmonary function. (a) The balloon lung model[28] has (b) direct physiological counterparts in the human respiratory system.

To help the students understand the above-mentioned key concepts of pulmonary functions, instruct the students to do experiments and comparisons using the balloon lung model as follows:

(1) Lung structure: Compare the balloon lung model (Figure 5a) with the virtual 3D lung visualized in Lung Activity 1 (Figure 4). Ask the students to clearly tell which parts of the balloon lung represent lung, chest cavity, rib cage, windpipe, and diaphragm. The purpose is to reemphasize the key anatomical features of the human lung.

(2) Pulmonary function: Ask the students to move the handle at the bottom of the balloon lung in and out and to feel the airflow at the top nozzle, which mimicks the opening at the windpipe. Describe what happens to the two balloons representing left and right lungs. The purpose is to provide direct visualization of the inhalation and exhalation process similar to the realistic physiological respiration with the lung volume changes driven by the movement of the diaphragm. As a follow-up activity, ask the participants to breathe in

and out slowly and feel their chest motion as the indicator of lung expansion and contraction.

(3) Syndromes caused by restrictive lung diseases: Replace the original balloons with other stiffer ones that have higher Young's modulus. Ask students to feel the ease or difficulty to inflate the balloons compared with the previous ones. The purpose is to use the new balloons to represent the increased stiffness of the lung caused by restrictive lung diseases, including asbestosis, sarcoidosis, and pulmonary fibrosis. Convey the concept to the students that breathing difficulty will be induced when the lung becomes stiffer than usual. Subject to the same muscle strength to create the same pull force, the stiffer lung is harder to inflate.

(4) Syndromes caused by obstructive lung diseases: Ask the students to add different amounts of water into the balloons to mimic the increased secretion of mucus in lungs with obstructive respiratory diseases, such as chronic obstructive pulmonary diseases (COPD) including chronic bronchitis and emphysema. Ask the students to compare the ease or difficulty of inflating the balloons with and without additional water. Convey the knowledge that COPD and other obstructive respiratory diseases can lead to the blockage of the airways due to the increased mucus secretion, which also leads to breathing difficulties.

Lung Activity 3: Bowling through Airways Game to Understand Targeted Drug Delivery

Obstructive and restrictive lung diseases can exacerbate and lead to lung cancer. To treat lung cancers, it would be helpful to achieve targeted delivery[31] of chemotherapeutic particles directly to lung tumors rather than applying tumor-killing medications to healthy tissue (Figure 6a). Severe side effects occur if chemotherapeutic particles are delivered to healthy tissues. With a clear understanding of particle and fluid movements through the lungs, chemical engineers can find a way to "guide" the drug particles to designated lung sites. Metaphors such as shooting a 3-pointer in basketball can be used to illustrate the challenge of the targeted delivery. We designed the bowling through airways game to get students active and engaged in understanding how to modulate particle characteristics and coordinate drug inhalation conditions to achieve the targeted delivery. In the bowling through airways game, compare different types of balls for targeted bowling in a complex geometry (Figure 6b, c). As the sketch is shown Figure 6b, a two dimensional (2D) single branch or bifurcation is mapped using duct tape, representing an airway segment with the bifurcating feature. A fan is placed at an arbitrary angle and should be be turned on at different levels to simulate the pulmonary airflow during the inhalation of drug particles. Participants release different types of balls (i.e., the "drug particle") at the entrance of airway to target lung tumor Aims 1 and 2 marked in Figure 6b. The aims are represented by bowling pins. Pins can be positioned at different locations for additional exploration. Suggested options of the balls with different density, diameter, surface-area-to-volume ratio, and surface roughness are listed in Table 2. The activity introduces a couple of simplifications from the physiologically realistic pulmonary air-particle dynamics, i.e.,

(1) the on-floor 2D airway sketch is a simplified version of the 3D anisotropic moving airway domain in human lungs and

(2) the friction between the ball and the floor is considered equivalent to a lumped surface force comparable to the surface forces acting on the drug particles in human respiratory systems.

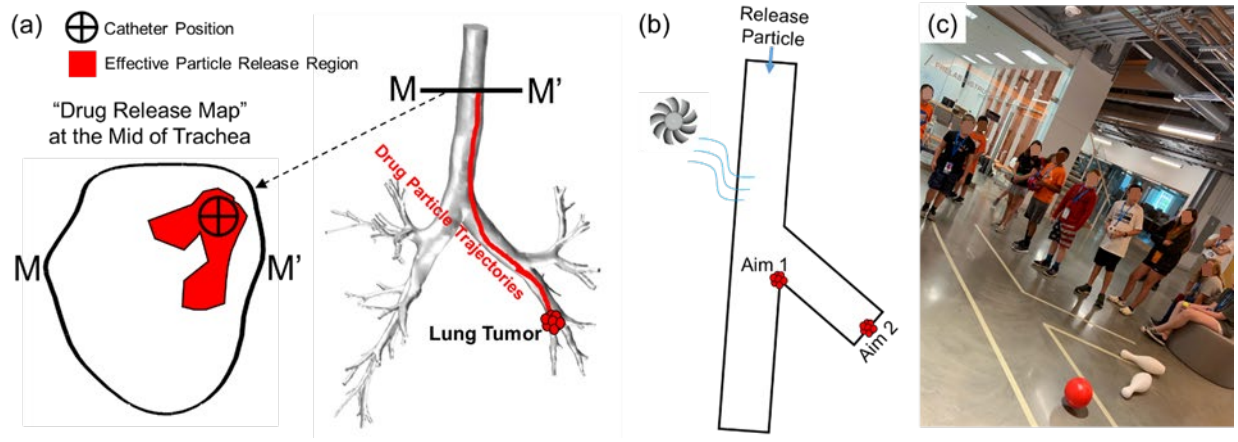

Figure 6: Targeted pulmonary drug delivery activity. To demonstrate (a) the concept of targeted delivery of chemotherapeutic particles to lung tumors, we designed (b) the bowling through airways game where spherical objects are bowled through physical representations of airways to target locations Aim 1 or Aim 2. (c) Participants attempted to use a hollow plastic ball to hit the bowling pin in location Aim 1.

Table 2: Selection of balls with different characteristics to simulate drug particles in the bowling through airways game.

Ball Type	Density [kg/m^3]	Diameter [m]	Surface-Area-to-Volume Ratio
Soccer	79.82	0.220	27.3
Plastic Bowling	568.54	0.216	27.8
Pilates	13.91	0.650	9.2
Dodge	77.70	0.216	27.8
Tennis	340.14	0.068	88.2
Ping Pong	80.57	0.040	150.0
Massage	588.52	0.075	80.0
Marble	79.82	0.220	27.3

Ask the students to select a ball and roll the ball (drug particles) to either knock over the pins (targeted tumors) or hit them. Each student can try multiple times with one or more ball selections. The ball should not cross the airway boundaries. This constraint represents the particle impacting an airway wall and sticking there. During the trials, emphasize the following concepts:

(1) Several key mechanisms lead to particle deposition, e.g., inertial impaction, gravitational sedimentation, and diffusion. Their relative importance in particle transport is related to particle size, density, and particle surface roughness. Particles need to avoid deposition in the upper airway, so that they can reach the designated lung sites.

(2) Multiple types of forces acting on the particles can influence the particle trajectories. The body force (gravity) will be more dominant for particles with large size and density. The surface force (air drag) will be more dominant for particles with a high surface-area-to-volume ratio.

(3) Controlling the particle trajectories is more challenging when targeting a more distal airway position (e.g., Aim 2).

To guarantee the success of conveying the above-mentioned key points to the participants, ask them to try and observe the trajectories of different types of balls and answer the following questions:

(1) What can cause the "particle" to turn its moving direction?
(2) Is a large particle easier to be redirected?
(3) Is a light particle easier to be redirected?
(4) Does the release position influence the trajectory?
(5) Does the release speed influence the trajectory?
(6) Does the spin influence the trajectory?

Lung Activity 4: Lung Aerosol Dynamics Simulations to Introduce In Silico Pulmonary Healthcare

To connect all activities to the future real-world clinical practice, representative lung aerosol dynamics simulation cases are presented to the participants as the summarization of the lung activities. The objectives are to

(1) Introduce the concept of *in silico* pulmonary healthcare and the unique capability of simulations to predict airflow and particle transport, deposition, and translocation through human respiratory systems based on physics principles.
(2) Discuss the advantage to integrate the computational fluid particle dynamics (CFPD) method into lung disease treatment planning. Specifically, using CFPD simulations in subject-specific human respiratory systems is noninvasive, cost-effective, and time-saving, which is able to provide personalized treatment planning to maximize the therapeutic outcomes and minimize side effects.
(3) Inspire the participants by showing the potential of engineering and science knowledge on improving human health and living quality.

Cases studies from our research that are covered include

(1) Steps to reconstruct 3D human respiratory configuration from clinical data, i.e., CT/MRI images of patients[32]
(2) Achieving lobe-specific targeted delivery of aerosolized drugs[31]
(3) Immune system response to influenza virus inhalation and infection[33]

For the next offering of Grandparent University, the lung activities will be expanded with two newly designed hands-on modules.

New Lung Activity 1: LEGO® Lung Models

The goal of this newly designed activity is to provide participants a hands-on experience on "reconstructing" lungs using LEGO bricks (comparable to pixels in the real reconstruction of the 3D airway geometries based on CT/MRI scanned images) to strengthen their knowledge on the key anatomical features of the human respiratory systems.

Using the open-access software LEGO Digital Designer[34], digital airway segments will be customized and designed, which consist of basic LEGO® bricks (see Figure 7 as an example). Digital LEGO lung model designs will include both healthy and diseased conditions. With the blueprints designed by the authors, students will be provided with sufficient numbers of LEGO building bricks to build their own LEGO lung models. Teams will be asked to compare healthy

and diseased LEGO lung models and identify the anatomical changes such as obstructions in airways, breakdown of the septum in alveoli, and thickened airway walls due to inflammation. Compared with the current activity (Lung Activity 1 in Figure 4), the LEGO® lung model activity will provide additional ways for the participants to study anatomical features of human respiratory systems leveraging the following aspects:

(a) Kids are familiar with LEGO bricks, and many love to play with LEGO.
(b) LEGO bricks have different colors, which can differentiate healthy and diseased sections of the lung. Different colors can also make kids familiarize themselves with the "color maps" commonly used in computational and experimental result visualization of "variables" with different values.
(c) Using different building strategies to mimic the surface roughness of the inner airway walls is possible.
(d) The LEGO lung models can also be extended to introduce small particles to try targeted delivery ideas in LEGO airways. The particles can be iron particles so that participants can use magnets to mimic the influence of electromagnetic force to control the trajectories of the particles and target specific regions in the lung.
(e) With the convenience of dividing LEGO lungs into different regions, key lung structure features can be easily observed such as the number of lobes, angles between trachea to daughter tubes, the structure of alveoli, and geometric dimensions.

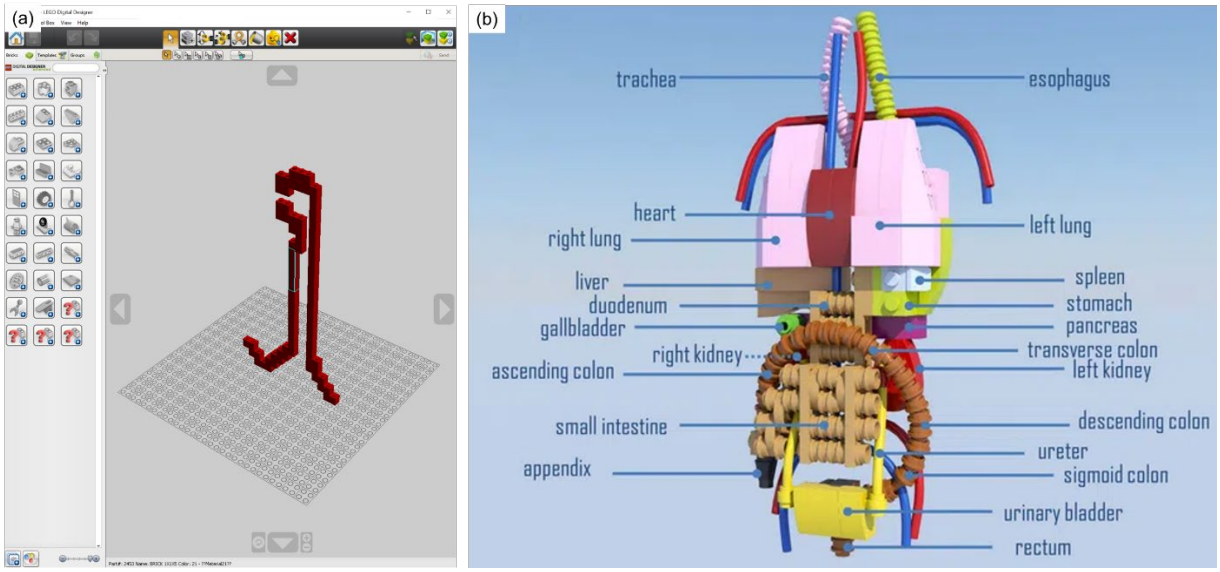

Figure 7: Examples of LEGO lung design software and anatomy. (a) Graphic user interface of open-access LEGO Digital Designer[34] will be used to design LEGO lung models, which will be assembled by participants using LEGO bricks. (b) The commercialized LEGO product idea "Anatomini" is an example for human anatomy study.

New Lung Activity 2: Visualizing Inhaled Air-Particle Flow Dynamics Using Virtual Reality

Collaborating with Ansys Inc. (Canonsburg, PA), we are developing virtual reality (VR) apps for compatible visualization for K-12 students and the general public to have a better view of complex pulmonary airflow and particle transport dynamics (Figure 8). Snapshots from the beta version of the app are shown in Figure 8, from a fixed view following an inhaled particle through the pulmonary route. The VR will provide an immersive display experience that will allow

participants to digitally probe the airway structures, visualize the 3D pulmonary airflow field, track inhaled particle trajectories, and examine the differences in lung motion with or without lung diseases. The VR software, working with commercially available VR goggles, will give the user the capability to "follow" the inhaled air and particle traveling through the pulmonary route. All the visualized results will be from simulation results in the last author's lung aerosol dynamics research. Demonstrations of the VR app and dissemination of the simulation results will be provided accordingly. The VR module will be downloadable for educators and the public. The last author can be contacted directly for more information.

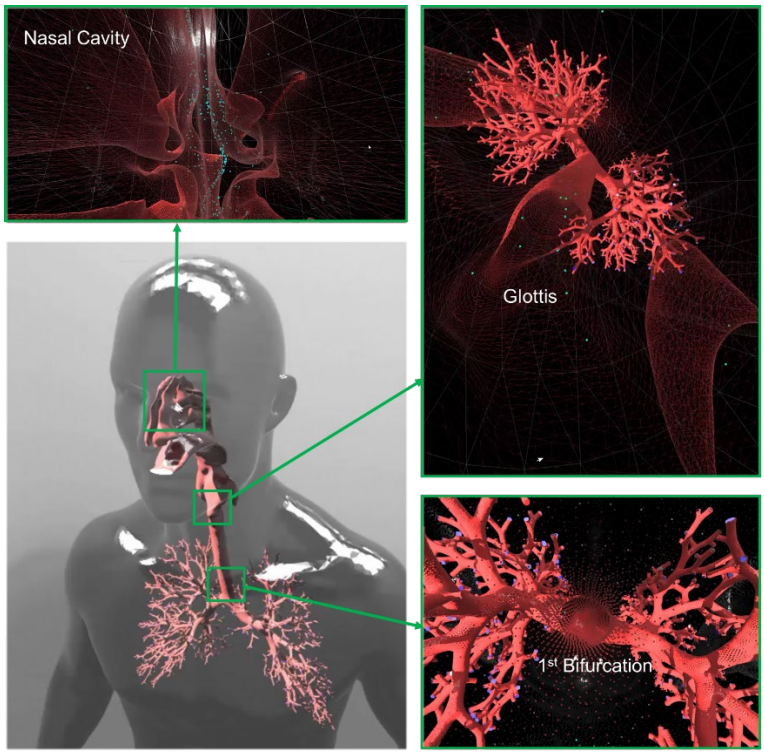

Figure 8: Snapshots of virtual reality (VR) views while traveling through pulmonary routes in the beta version of the VR app set to be released later in 2021.

Experiences

We did not formally assess the lesson plan through a pedagogical research study. Our primary events for using the activities were managed by other organizations. The logistics made it difficult to obtain parental permissions for conducting a human subjects research study on minors. Instead, here we have presented the activities developed that were refined after participant feedback. The summer camp surveyed their adult participants, but they had a small overall response rates and only limited feedback for our particular session. The written and verbal feedback was positive in both 2018 and 2019 so that were were invited to participate again in 2019 and 2020. For Kidney Activities 1 and 2, we adapted a series of hands-on experiments and demonstrations we previously developed for kids to learn about water filtration[16] to have a new emphasis on blood filtration in the kidneys and the engineering of artificial kidneys. See that publication[16] for full details on the experiment as well as the supplemental files including presentations and worksheets that are available online on our

website[35]. We added content to introduce the kidneys and their important role as filters to the presentation on water filtration. We found the video "What are Kidneys?"[15] to be well-done and age-appropriate for the children. Kidney Activity 2 is always popular as it gets participants actively moving. In our first version of the camp session in 2018, we only offered the kidney activities. General feedback was especially positive for Kidney Activity 4. Noticeably with the Grandparent University participants, these discussions to date have been full of empathy of the children for grandparents or other adults in their lives that have experienced the limitations of dialysis or kidney transplants. The intergenerational conversations were much different than in other middle school outreach settings the authors have taught in. These have been positive examples of participants considering the social implications of engineering and technology advances. Kidney Activity 3 was improved in the next camp by including the 3D printed devices to supplement the Carolina Biological Supply kits. Additionally in the first version, we included computational activities originally designed for high school and college students[13, 14]. We did not adapt these appropriately to the middle school and senior adult audience, and the participants did not rate the computational activities favorably. Thus, we removed them in the second offering of the camp in 2019 and instead incorporated the hands-on lung activities. The participants really liked Lung Activity 1. It was so enthusiastically received that the participants spent more time on it that anticipated because they were enjoying themselves so much. Lung Activities 2 and 4 will continue to be refined as we interact with more participants. Lung Activity 3 was well-received as an active game that lets students release energy. New Lung Activities 1 and 2 have yet to be tested in the camp setting, but they were developed in order to expand the repertoire of lung activites that one of the authors could use in future spin-off events focused primarily on the lungs. We were scheduled to teach the camp a third time in 2020, but it was cancelled due to the COVID-19 pandemic.

Collectively, the sessions that we were able to develop along with those of colleagues in our department who we mentored to develop their own energy and materials related sessions in 2019 expanded the scope of the engineering offerings at the Grandparent University summer camp. The camp is not STEM-focused, but we helped in growing the STEM representation and popularity among the available "majors". We have not yet seen the impacts of collegiate chemical engineering enrollment through these specific outreach events because of the age of the student participants. However, by educating the grandparents on STEM activities and careers, there may be more immediate trickledown effects on STEM aspirations and career awareness by word of mouth among their families, friends, and communities[3]. With this paper, we also aim to extend the impact of our outreach efforts beyond our local institution.

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Appendix A: Learning Objectives

After completing this lesson, students will be able to

- Define filtration and pores.
- Describe differences between mechanical size-based filtration and chemical filtration via adsorption.
- Describe the importance of filtration by the kidneys.
- Explain how damaged kidney filters can be detected in clinical practice.
- Describe one or more opportunities for chemical engineers to design improved filters to treat patients with kidney disease.
- Define key anatomical features of human respiratory systems.
- Describe differences in breathing capabilities in healthy and diseased lungs and the changes in airway structures and functions caused the problems.
- Describe the defense mechanisms of human lung airways to protect the intrusion of inhaled toxic particles.
- Identify the strategies that can be used to deliver medicinal particles to designated "lung sites."

Appendix B: Background Relevant to the Learning Objectives

Filtration is a process for removing contaminants from a fluid by passing it through a filter, which could be one object with pores or one or more layers of a porous material. Pores are openings or holes in the filter materials and are important for separating solid contaminants. In the lesson, we introduce two types of filtration: mechanical filtration and chemical filtration (also known as adsorption). Mechanical filtration depends on pores to allow only fluids and solid particles that are smaller than the pores to flow through the filter, blocking larger solid particles. Chemical filtration depends on interactions between dissolved molecules in the fluid and the surfaces of the filter materials. Dissolved molecules can stick to the filter medium independently of pore size. In the human body, kidney filtration is an important waste removal process and helps the body maintain the proper balance of water, salt, and glucose in the blood. Kidney filtration involves both pore-size-dependent mechanical filtration and molecular-interaction-dependent chemical filtration processes. The nephron, the functional unit of filtration in the kidney, removes waste from the blood while keeping important compounds needed for a healthy body. The nephron has two major zones. First, the glomerulus of a nephron is a bundle of capillaries surrounded by a capsule and lined with specialized filtration cells. Through pore openings and chemical diffusion, the blood traveling through the capillary is filtered of its waste. Then in the tubule, the second zone of the a nephron, fluid and molecules are selectively reabsorbed into the blood. What remains at the exit of the tubule is collected and excreted as urine. Because each glomerulus is so important in blood filtration, the thousands of glomeruli are major components in kidney health and important for research studies related to filtration in the body. In certain kidney diseases, large molecules such as proteins leak through damaged glomeruli and are detectable in the urine. Chemical engineers can help to treat patients with kidney disease by designing improved filters and other equipment for dialysis machines, external artificial kidneys, and internal artificial kidneys.

The lungs have an airway system that consists of multiple branches. Each branching level is called a generation that is denoted as "G" followed by a number that increases for each subsequent branch beyond the trachea to distal alveoli at generation 23 (G23)[36, 37]. Key anatomical features include a 90-degree bend connecting the oral cavity/nasal cavity and the pharynx, contraction at the glottis, and the cascade of branches of lung airways extending into 5 lobes with a cardiac notch in the left lung. Obstructive and restrictive lung diseases, such as chronic obstructive pulmonary disease and asthma, can significantly alter the anatomical features and pulmonary functions. Key alterations include reduced airway lumen, increased secretion of mucus, damaged alveoli septum (dividers between the alveoli), and increased lung-stiffness-induced breathing difficulties. Human airways are lined with mucus that is sticky so that it can trap inhaled particles, bacteria, viruses, and gases and clear them from the respiratory system. When this process works perfectly, we can stay healthy. Sometimes the exposure is too strong or extends for too long allowing the lungs to become infected or damaged. In these cases and for other diseases that develop in the lungs like cancer and asthma, there is interest in using aerosols to deliver medications directly to the lungs by inhalation. Then the mucus and the complex geometry of the airways become a challenge to overcome with engineering strategies that require understanding of the fluid mechanics of air, mucus, and drug particles. Inhaled particle transport through the inhaled pulmonary route is controlled by multiple factors including particle size, density, and shape and forces and their types (i.e., surface force or body force) acting on the particles such as gravity, airflow drag and lift as well as other external forces such as electromagnetic force and acoustic force[38-42]. Balancing those factors can help the particles avoid striking the upper airway walls and penetrate deeper into the lung, which is beneficial for certain medications.

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