A qualitative analogy for respiratory mechanics

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The geometric configuration and mechanical properties of the integral elements of the respiratory system, as well as the modus operandi of the interacting parts in the ventilation process, comprise a hard-to-visualize system, making the mechanics of pulmonary ventilation a really confusing topic for students and a difficult task for the teacher (1, 9, 10, 13). To clarify, consolidate, or even gain a broader view of this issue, didactic models using balloons (3), a bottle of water (11), a glass airtight cylinder (9), and computer software (1) have been described in the literature, providing excellent pedagogical tools. However, these tools are designed to be applied after a theoretical approach to the issue has already been given in the classroom. Here, to improve and facilitate the learning-teaching process during theoretical classes, an analogy for respiratory mechanics is presented. The features of two very familiar elements, syringes and springs, and their predictable behaviors are systematically mapped onto the interacting parts of the respiratory system and the ventilation process.

To introduce this analogy, it is important to consider the following points. First, expansion of the lungs is carried out by skeletal muscle contraction, but there is no direct connection between the respiratory muscles and the lungs. Second, the lungs are very elastic structures. Third, even at minimum pulmonary volume the elastic components of the lungs are stretched and therefore tend to recoil. Fourth, the ligaments at costovertebral joints, such as the radiate and costotransverse, are elastic and tend to recoil during respiratory excursions of the chest wall, pulling the ribs to a given position of equilibrium. Fifth, between these two elastic structures (the lungs and the chest wall) there is a hermetic space: the pleural cavity. The mechanical behavior of this airtight space follows Boyle’s law, meaning that its pressure is inversely proportional to its volume. Sixth, the visceral and parietal layers of the pleura, the sealing structures of the pleural cavity, are tightly attached to the lung surface and to the internal surface of the chest wall, respectively. In this way, the movements of either the lungs or chest wall change the volume of the pleural cavity and, hence, intrapleural pressure. Finally, during embryogenesis, the pulmonary epithelium secretes liquid within the lungs, so they are fluid-filled structures (7). This liquid exerts an internal distending pressure on the lungs, which overcomes the elastic lung recoil, maintaining them in a distended state throughout fetal life. At birth, the replacement of this liquid with air by aeration removes the distending pressure and generates surface tension at the air-liquid interface. These events greatly increase lung recoil, causing the lungs to collapse away from the thoracic cage. As a result, intrapleural pressure is ~5 cmH₂O below atmospheric pressure.

Here, we take these seven elements together and gradually organize them into a simple analogy to explain to undergraduate students the movements of the chest wall and lungs that underlie alveolar ventilation. Figure 1 shows the framework of the model, which consists of a syringe and a pair of springs. To set the basic configuration, it is necessary (Fig. 1A) to 1) cut the needle coupler (dotted line) of the syringe, 2) cut the remaining tip from the barrel (dashed line), 3) make a hole in the center of the barrel (arrow) with a diameter smaller than the inner diameter of the needle coupler, and 4) solder the needle coupler over the hole (Fig. 1B). The next step is to introduce another plunger through the opened end of the barrel and then close the needle coupler to make a sealed space between the rubber plunger heads (Fig. 1C). This setup allows students to visualize, in a very intuitive manner, how the movements of two physical structures can be coupled by pressure differences.

In a simple example, when the right plunger (RP) is pulled, the left plunger (LP) slides passively inside the barrel, following the movement (Fig. 1D). This can be explained by Boyle’s law: as the RP was pulled, the volume of the airtight space between the rubber heads increases, and, consequently, pressure decreases proportionally, becoming less than atmospheric pressure. The force generated by the pressure difference pushes the LP, so that it follows the RP’s movement. This same principle governs biomechanical interactions between the chest wall and lungs, i.e., even though there is no solid ligament between these two structures, their movements are coupled together by the pleural cavity. To start building an analogy between the two-plunger syringe system and the respiratory system, let us consider the LP and RP as the lungs and chest wall, respectively. Specifically, we can correlate the movements of the plungers with breathing movements of the lungs and chest wall. In this sense, we refer to the LP and RP as the LPₚ and RPₚₚ, where the subscripts LP and RP denote the lungs and chest wall, respectively. Also, the rubber heads represent the pleural layers. Note that the rubber heads are firmly attached to the plungers, just as the pleural layers are attached to the chest wall and lungs.

To improve the model, we can introduce an elastic component. As we have pointed out, both the lungs and chest wall present elastic properties, which are modeled by a pair of springs coupled to the thumb rests of the plungers (Fig. 1E). By stretching the springs and fixing their ends (Fig. 1F), we can obtain a configuration from which we make the following considerations. As the plungers are pulled by stretching the springs, the volume of the sealed space between the rubber heads increases, creating a compartment of subatmospheric pressure (just as intrapleural pressure at birth). This negative pressure exerts vacuum traction over both rubber heads (dashed arrows in Fig. 1F) with a tendency to hold them...
Fig. 1. Framework of the model. By cutting (dashed line) the tip from the barrel of a syringe (A), welding the needle coupler over a hole (vertical arrow) in the center of the barrel (B), and introducing another plunger, we make up a hermetic space between the rubber heads (C). This configuration “attaches” the movements of the plungers to each other with no physical ligament (D). The coupling of a pair of springs to the plungers (E) generates subatmospheric pressure in the interrubber space, putting the system at a resting dynamic equilibrium position (F). The opening of the sealed space detaches the plungers (G). The horizontal arrows represent the forces acting over the system, where the solid arrows show the elastic restoring force and the dotted arrows show the pressure gradient force. In analogy, the left plunger (LP₁) represents the lungs, the right plunger (RP₁) represents the chest wall, the left spring (LS₁) represents the elastic component of the lungs, the right spring (RS₁) represents elastic component of the chest wall, and the open space in the syringe represents the pleural cavity (PC).

To highlight the key role played by negative intrapleural pressure in keeping the lungs expanded and to couple the chest wall to the lungs, an extreme example of a perturbation in our didactic model is shown in Fig. 1G, in which we take out the lid from the needle coupler, opening the interrubber space to the atmosphere. The students can readily suppose that this action immediately “disconnects” the plungers from each other, so the elastic recoil of the springs moves them away, putting the system at thermodynamic equilibrium. (This example simulates what happens during pneumothorax, when one of the pleural layers is perforated.)

Now, let us implement the model so that we can remove the system from the resting dynamic equilibrium position, similar to the respiratory system during breathing. It is an element capable of actively pulling the RP₁ away from the LP₁. To install it, we fix an inflexible bar at the thumb rest of the RP₁ as well as a pair of twines, which run through a pulley (Fig. 2A). Note that because the twines are flexible, the only way to trigger this system is by pulling the twine down. Sequentially, this action (Fig. 2B) pulls the RP₁ to the right, increases the volume and decreases the pressure of the interrubber plunger space, and pulls the LP₁ to the right, further stretching (following Hook’s law) its coupled spring. At the end of this excursion of the plungers (Fig. 2B), the restoring force of the LS₁ exactly equals the active traction exerted over the RP₁. A more negative pressure is generated in the space between the rubber heads to hold the plungers at this point of dynamic equilibrium. It is very easy for the students to figure out what happens if we release the active force from the right plunger: the elastic potential energy stored in the LS₁ is released, converted into energy of motion, which brings the system back to the resting dynamic equilibrium position (Fig 2A). Turning back to the analogy, pulling the twine down matches the contraction of the inspiratory muscle (Fig. 2) that moves the thoracic cage out and up, expanding the lungs. The releasing of the active force corresponds to the inspiratory muscle relaxation and the elastic recoil of the LS₁ to the passive recoil of the lungs during the expiration process.

To better represent the process of inspiration, we can use another pair of springs to counteract the outward movement of the RP₁ when it exceeds ~75% of its maximum outward pressure gradient force. In analogy, the twine (the active component) represents the inspiratory muscles (IM), right movements of the plungers represent the expansion of the thoracic cage and lungs, passive movements of the plungers to the left represent the retraction of the lungs and chest wall, and the resting dynamic equilibrium position represents the end of a resting expiration.

Fig. 2. Active and passive components of the model. By pulling down the twine (the active component), the system leaves the resting dynamic equilibrium position (A); both plungers move to the right (B). By releasing the active force, the elastic recoil of the left spring (the passive component) backs the system to the resting dynamic equilibrium position. The length of the arrows represents the intensity of the forces acting over the system, where the solid arrows show the elastic restoring force and the dotted arrows show the pressure gradient force. In analogy, the twine (the active component) represents the inspiratory muscles (IM), right movements of the plungers represent the expansion of the thoracic cage and lungs, passive movements of the plungers to the left represent the retraction of the lungs and chest wall, and the resting dynamic equilibrium position represents the end of a resting expiration.
excursion. Moreover, the three springs are now attached to the RPCW through twines, allowing the plunger to move at some extension in one direction without stretching one set of the springs (Fig. 3A). As shown in Fig. 3B, at ~75% of the maximum outward excursion the RPCW reaches its equilibrium position, at which point the coupled springs are not stretched. To further outward excursion (Fig. 3C), the applied force needs to overcome not only the restoring force of the LSL but also the force from the pair of small springs directly attached to the RPCW. In analogy, the three springs connected to the RPCW represent the ligaments in the costovertebral joints, which are not stretched when the chest wall reaches ~75% of its maximum outward excursion. The elastic recoil of the lungs and the traction exerted by the respiratory muscle contraction are the forces that move the ribs from this equilibrium position.

Finally, we can incorporate into the analogy two additional components to help the students understand the role of muscle and lung mechanics on alveolar ventilation (Fig. 4). The first component comprises the expiratory skeletal muscles, which are recruited in a forced expiration. They are represented by a pair of twines attached to the RPCW and run through pulleys (Fig. 4B). Activation of this system actively pushes the RPCW to the left, which increases the pressure in the interrubber head space, pushing the LP1. The second component comprises the alveoli, where gas is exchanged. They are represented by a single compartment, the hollow barrel of a syringe that we will refer to as the alveolar compartment (AC). The plunger of the syringe of the AC is attached to the LP1 by a pair of inflexible bars (Fig. 4B). This configuration ensures that the plunger of the AC follows the movements of the LP1 in both direction and without delay. Figure 4 shows the maximum excursions of the RPCW, which leads to maximum variations of the volume of the alveoli.

Fig. 3. Equilibrium position of the right plunger. At the resting dynamic equilibrium position (A), both large springs are stretched. At ~75% of the maximum right excursion of the plungers (B), no elastic energy is stored in the right plunger’s springs. Further outward excursion stretches the pair of small springs that pulls the right plunger to the left (C). The releasing of active force backs the system to the resting dynamic equilibrium position. The length of the arrows represent the intensity of the forces acting over the system, where the solid arrows show the restoring force and the dotted arrows show the pressure gradient force. In analogy, the right springs (RS_{CW}) represent elastic components of the thoracic cage.

Fig. 4. Active process for maximum and minimum excursions of the plungers. The system is implemented with a second barrel [representing the alveolar compartment (AC)] and a pair of twines to actively push the right plunger to the left [representing the expiratory muscles (EM)]. From B to C, the action of the active system (IM) leads to maximum expansion of the AC. From C to A, the active system (EM) leads to maximum contraction of the AC. The length of the arrows represents the intensity of the forces acting over the system, where the solid arrows show the elastic restoring force and the dotted arrows show the pressure gradient force. In analogy, the second barrel represents the AC and the active system represents the EM.
the AC. Beginning from where the model matches the end of a resting expiration (Fig. 4B), we first trigger the active system that pulls the $R_{PCW}$ to the right, reaching its maximum right excursion (Fig. 4C). We then turn off this system and trigger that pushing the $R_{PCW}$, so that the plungers reach their maximum left excursion (Fig. 4A). Note that during the excursions of the plungers, the volume of the AC is changed proportionally, leading to inverse variations in AC pressure (becoming less than atmospheric pressure during volume expansion and greater than atmospheric pressure during volume retraction). This pressure gradient drives an inward air flux during AC volume expansion and an outward air flux during AC volume retraction through the opened end of the AC. In analogy, the full excursion of the plungers models the biomechanical interactions of the lungs, pleural layers, and chest wall taking place during a most forceful inspiration and a most forceful expiration. Furthermore, the air flux through the opened end of the AC matches the air flux through the air pathways during the inspiration and expiration processes. Note also that at maximum left excursion of the plungers, the $L_{S_m}$ is yet stretched and the AC is not empty, meaning that at the end of a most forceful expiration, the lungs are yet expanded and filled with some amount of air (residual volume).

I have used this analogy as an instructional tool in theoretical classes to teach respiratory mechanics to undergraduate students from different programs. My classroom experience led me to share the opinion of other educators in that respiratory mechanics have always been a difficult topic for students to comprehensively understand (1, 9, 10, 13). This difficulty is probably due to the dynamic nature of the mechanic relationships and complex configuration of the interacting parts during the respiratory process. Some points, such as the absence of a direct connection between the respiratory muscles and lungs, the relationship between the pressure of the pleural cavity and volume of the lungs, and the balance of elastic restoring forces and how the contraction of skeletal muscle alters the pressure of the pleural cavity, are unfamiliar to students, making it difficult for them visualize the modus operandi of the system. Another factor, as pointed by West (13), is that apparently students do not bring from high school and college a strong background in elementary physics, which is crucial for a quantitative view of the mechanics of breathing. To improve learning outcomes of students in respiratory mechanics, the literature has a number of excellent didactic models (1, 3, 9, 11), which are designed to be applied in practical classes. However, because respiratory mechanics are not always covered with practical classes (more often, students are directed to the topic of the regulation of breathing), or because practical classes are difficult to implement with large numbers of students, or even because any student, regardless of reason, is unable to carry out the practical task, it is imperative, in such cases, that the student achieves a consistent conceptualization of the mechanisms of pulmonary ventilation during theoretical classes. Based on works suggesting that analogy-based pedagogy, when used properly, can both improve teaching performance (8) and help make science concepts meaningful to students (4, 12, 5), as well as on my own experience (2), I drew this analogy to be applied in theoretical classes. The analogy highlights critical points, such as the active and passive elements of the ventilation process and the key role played by subatmospheric pressure of the pleural cavity. Because springs and springs are well-known elements, the students can predict with certainty the functioning of the analogy model. Also, the students can easily recognize the similarities between the model and the respiratory system. These features of an analogy facilitate the learning process: they help students to build meaningful relationships between what is already known and what is they are setting out to learn, playing a critical role in constructivist views of learning science (4–6). During the explanation of the ventilation process, the two domains of the analogy, i.e., the physical (the model) and the biological (the respiratory system), are systematically compared. Figures 1–4 can be gradually introduced through a PowerPoint presentation or, as I prefer, drawn on the blackboard. Figure 1 works as a template over which new elements can be incorporated and correlated, as the explanation progresses, with the components of the pulmonary ventilation. The design of the model helps students to visualize the configuration of the various components of the respiratory system, and the analogical reasoning guides their understanding of how these elements interact with each other during the ventilation process. Even though an analytic assessment of the practical effects in the classroom is lacking, our perception is that students have an immediate acceptance of the analogy model. The familiar and predictable behavior of the model as well as its easy correlation with the respiratory system strongly gain the students’ attention. When the students were asked if the analogy helped them to visualize and understand the mechanics of breathing, they invariably said “yes.” The students themselves, in a positive feedback during the explanation, made correlations between the two domains of the analogy. I also feel that the analogy makes my explanation much easier; I make myself more readily understood. Finally, we must emphasize that this work does not advocate or leave out the practical classes or the quantitative approach. When the teacher does not count on practical classes, this analogy can work in an alternative way. And if the practical classes are in place and the teacher can work with the concepts of physics, this analogy can also be useful in performing a preliminary qualitative exploration.

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REFERENCES


