

LAPLACE'S LAW AND THE ALVEOLUS: A MISCONCEPTION OF ANATOMY AND A MISAPPLICATION OF PHYSICS

Henry D. Prange

Medical Sciences Program, Indiana University, Bloomington, Indiana 47405

Both the anatomy and the mechanics of inflation of the alveoli, as presented in most textbooks of physiology, have been misunderstood and misrepresented. The typical representation of the acinus as a "bunch of grapes" bears no resemblance to its real anatomy; the alveoli are not independent little balloons. Because of the prevalence of this misconception, Laplace's law, as it applies to spheres, has been invoked as a mechanical model for the forces of alveolar inflation and as an explanation for the necessity of pulmonary surfactant in the alveolus. Alveoli are prismatic or polygonal in shape, i.e., their walls are flat, and Laplace law considerations in their inflation apply only to the very small curved region in the fluid where these walls intersect. Alveoli do not readily collapse into one another because they are suspended in a matrix of connective tissue "cables" and share common, often perforated walls, so there can be no pressure differential across them. Surfactant has important functions along planar surfaces of the alveolar wall and in mitigating the forces that tend to close the small airways. Laplace's law as it applies to cylinders is an important feature of the mechanics of airway collapse, but the law as it applies to spheres is not relevant to the individual alveolus.

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Explanations of the mechanics of breathing at the alveolar level have been difficult to understand and teach clearly because of the difficulty in relating the properties of the lung to familiar and intuitively obvious analogous systems and because, in many cases, the structure of the lung has been incorrectly illustrated. The mechanical properties of the lungs are often poorly represented by the models drawn in textbooks. Most of these models rely on positive pressure for inflation and treat the alveoli as independent, balloon-like devices. In reality, neither of these assumptions is correct, and both lead to the misunderstanding of how the lungs work.

The lungs are inflated by negative pressure applied to the surface of the organ and do not resemble balloons at all in their structure at any level of their anatomy. The responses of the lungs to the forces of ventilation are a complex interplay among the mechanical properties of their spongy or froth-like tissue and the effects of surface tension of the fluid lining of the airways. Attempts to resolve these properties in terms of simple mechanical models like balloons and soap bubbles have led to treatments of the subject that may appear to be sophisticated and more readily understandable but bear little resemblance to the actual structure and function of the tissue. That the incor-

rect models continue to appear in textbooks is all the more remarkable in that the disparity between the balloon or independent bubble analogy and the actual mechanics of alveolar inflation was clearly and elegantly described in the literature decades ago (1, 7, 12, 13).

STRUCTURE OF THE LUNG

The important way in which the **alveoli resemble a froth rather than individual bubbles** is that they **share common walls** and that they are basically **polygonal** in shape; that is, the **walls are flat**. The requirement that the cells of the lung be open to the airways makes the pulmonary parenchyma more complex than a simple foam, but the analogy, for example the division of the volume with a minimal area of the walls, is still valid. A glance at a microscopic preparation, e.g., Fig. 1, will immediately confirm this observation. Despite being called an **acinus** (Latin for “bunch of grapes”), the actual anatomical arrangement of a group of related alveoli in no way substantiates this analogy. Neverthe-

less, in many textbooks not only is the structure literally called a “bunch of grapes,” it is shown to appear as such, e.g., Fig. 2. I do not know with certainty where this idea originated, but one possibility is as an artifact of older methods once widely used to make tissue casts using materials such as the low-melting-point metal alloy called Wood’s metal, a fusible alloy, consisting of one or two parts cadmium, two parts tin, and four lead, with seven or eight parts bismuth, that melts at 66–71°C (2).

To **make such a lung cast**, one must first evacuate the gas from it with a vacuum applied to the trachea or with positive external pressure, a point I will return to below, and then inject the heated Wood’s metal at a low pressure until the lung is reinflated. After cooling, the tissue is digested away to reveal the lung structure (Fig. 3). **As is often the case with casts**, the **injected material cools**, hardens, and **fails to fill completely** the portions **most distal** to the point of injection. But these parts of the cast, being at the surface

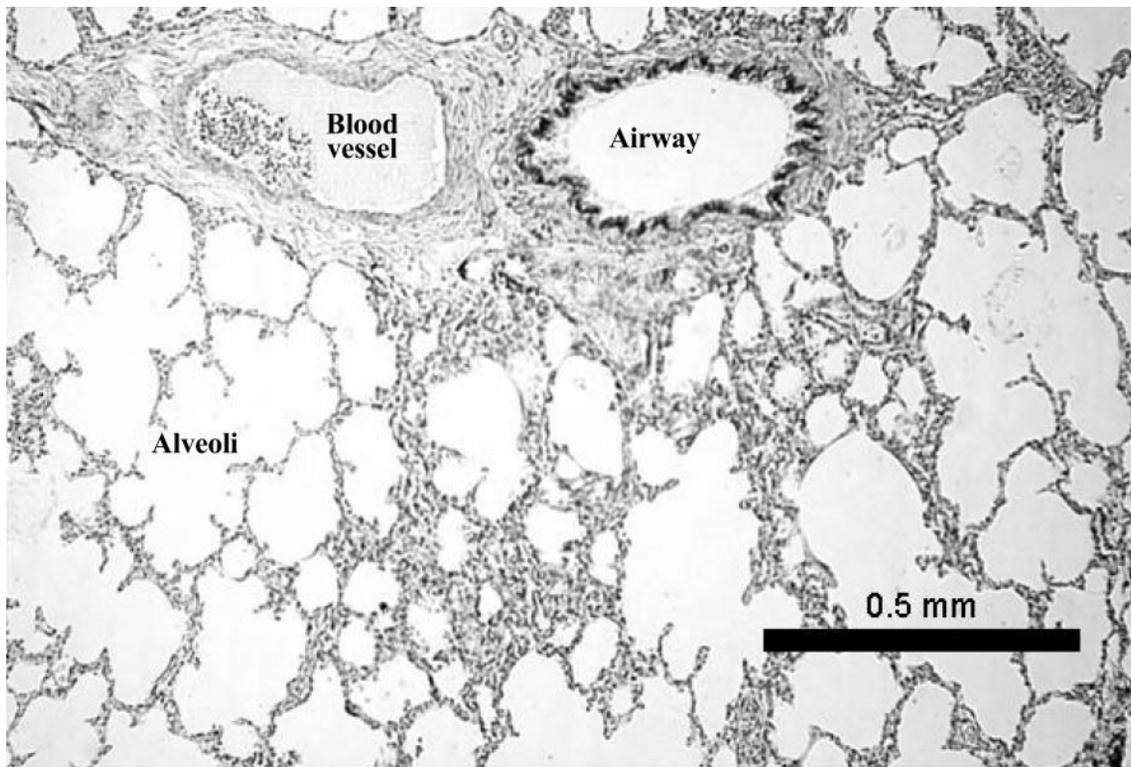


FIG. 1.

Section of human lung. Detail from an original slide generously provided by A. Mescher.

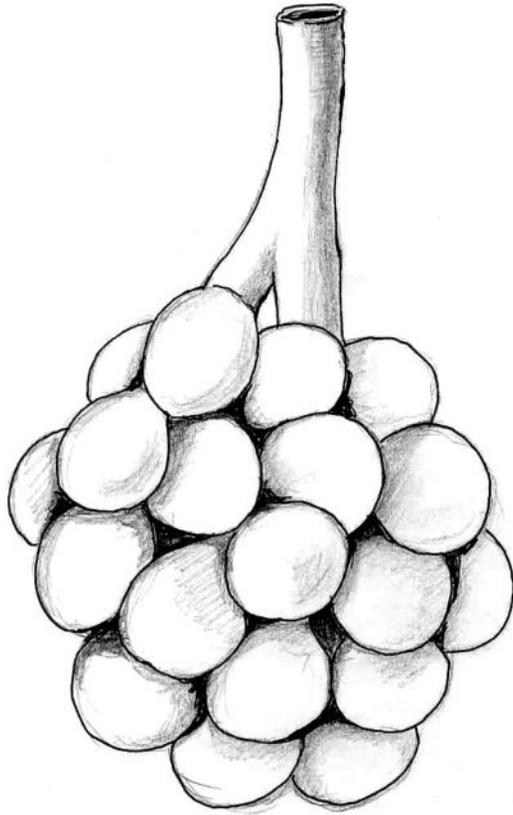


FIG. 2.

Structure of the acinus portrayed as a “bunch of grapes,” similar to the drawings found in most popular physiology and anatomy texts. Original artwork by L. Ferguson.

of the lung when the tissue has been removed, are the most visible. This view of the lung cast, with the terminal alveoli distended from the pressure of inflation, immediately demonstrates the resemblance to the “bunch of grapes.” This view also leads to the erroneous conclusion that the acini are isolated from one another in the lung.

Historically, the earliest reference that I have seen on the topic presented this view as the structure of the arrangement of the alveoli throughout the lung. Malpighi (6) scraped off the surface of the lung and then inflated and dried it, which must have resulted in the outward bulging of the remaining intact alveoli. He described the structure as being globular vesicles. He made the statement despite his drawing elsewhere in *De Pulmonibus* of a frog lung that clearly shows a

prismatic internal structure. Unfortunately, textbook writers (and I am surely among them in this practice) tend to copy what is in earlier volumes, especially in areas where they lack firsthand knowledge and, whatever the original source of the misconception, have perpetuated this erroneous view of lung structure.

The use of the bunch-of-grapes model that presents the acinus as an isolated structure persists in textbooks despite the fact that contrary illustrations often appear on the same page with the erroneous view. One need only look at the lung tissue in Fig. 1 to see that such a view is simply and obviously incompatible with the actual structure. Why has this view persisted despite evidence to the contrary? To find out, I think one must examine the mechanical forces involved in inflation of the lung at the alveolar level.

MECHANICS OF VENTILATION

We biologists often seem driven to seek the elegant and sophisticated mechanisms of physics in the far more complex structures of plants and animals. We are prone to fall into the trap of injecting physics into our work wherever we can, whether or not its use is justified or correct. In our models for explanation of lung mechanics, we lie caught in just such a snare.

The chest wall expands and pulls the surface of the lung with it via a fluid connection that is exactly the same as if one placed a balloon in one’s mouth and tried to inflate it by sucking on it, in which case the force is transmitted by saliva. This example is, by the way, the only similarity that the inflation of the lung bears to that of a balloon. The force on the lung surface is transmitted three-dimensionally throughout the tissue of the lung and causes it to expand in volume. This expansion is resisted to a lesser extent by the elastic properties of the pleura and airways but primarily by the matrix connective tissue between the alveoli (7, 9, 14). The delicate tissue of the lung is arrayed on this tensile matrix of connective tissue “cables” of elastin and collagen that are found at the septa (10).

The expansion of the lung, primarily at low lung volumes (8), is also resisted by the surface tension of the thin layer of fluid that may line the alveoli and airways, and therein arises a common misapplication



FIG. 3.
Close-up of a Wood's metal cast of a dog's lung. Photo by the author.

of the physical principle of the effects of surface tension of curved surfaces, known as Laplace's law.

Laplace's law states that the pressure inside an inflated elastic container with a curved surface, e.g., a bubble or a blood vessel, is inversely proportional to the radius as long as the surface tension is presumed to change little. A common illustration of this phenomenon is that the effort required to blow up a balloon is greatest when the diameter of the balloon is least.

Perhaps one of the most commonly repeated figures in discussions of the mechanics of ventilation of the alveolus is the Y-tube (an illustration that too readily suggests the trachea and bronchi) with unequal bubbles attached to its arms (Fig. 4). Typically, in an accompanying figure this apparatus is shown with one of the bubbles larger and the other collapsed, often drawn to resemble a shriveled lung. This dia-

gram, along with various forms of Laplace law equations is intended to show that, without intervention, a small alveolus ought to collapse and inflate its somewhat larger neighbor. Because all the "grapes" in the model cannot be of exactly the same size, without the aforementioned intervention the lung ought to collapse/explode in a series of several million pops. The intervention required, we are told, lies in the surfactant properties of the liquid lining, which, amazingly, acts so that it perfectly—and it must be absolutely perfect to work as suggested—alters the surface tension of the alveoli of different radii so that Laplace's law is exactly counteracted at any volume.

There is no question that the surfactant in the liquid in the lung reduces its surface tension along the flat and curved surfaces and that without it there is much increased resistance to inflation. That is not the point I am arguing here. However, the application of Laplace's law to the individual alveoli can have little

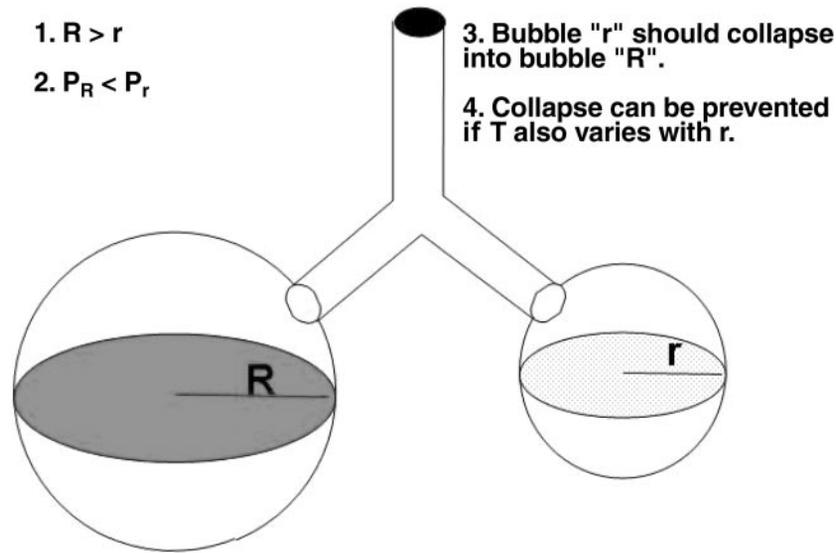


FIG. 4.

Laplace's law as it applies to bubbles of unequal radius attached to a Y-tube. The pressure (P) in a bubble is equal to 4 times the surface tension (T) divided by the radius (r). As applied to the grape-like alveolus, where only the inner wall has a liquid surface exposed to gas, the formula is $P = 2T/r$.

to do with the phenomenon, because not only are the alveoli not independent of one another, they do not have curved, much less spherical, walls. One can consider the outer shell of a larger portion of the lung as approximating a multifaceted polygon that approaches a sphere in shape and apply Laplace law considerations to inflation of that portion, but in so doing, the consideration is well beyond the interaction of adjacent alveoli. Furthermore, one must assume that only the alveolar walls on the periphery of the arbitrarily chosen portion of tissue are involved and that there is no tension across the chosen section, which is contradictory to the way the lung's elasticity works.

The walls of each alveolus are shared in common with those of adjacent alveoli. The patency of the alveoli is maintained by the tension through the matrix of connective tissue in opposition to the tendency of the walls to recoil and to the surface tension of the thin layer of fluid that lines the walls. Although regions or lobes of the lung may be partially collapsed, one alveolus cannot readily collapse into another, because it is not held inflated by positive pressure like a balloon but rather is held in place by its connective tissue framework. To collapse, an alveolus must over-

come in all directions the tension of that matrix, which increases as it becomes smaller and more forcibly resists further collapse (7). This pervasive, omnidirectional tension on any part of the lung tissue is called radial traction or interdependence. It is the tension of the adjacent tissue, not the amazingly perfect ability of surfactant to counteract Laplace's law, that prevents alveoli of differing sizes from collapsing into each other.

Furthermore, because of the prismatic nature of the cells in a froth and of the alveoli in the lung, the only curved part of the alveolar wall is that which occurs from fluid accumulation in angles where the walls intersect. Some texts represent the alveolus as having flat sides but with the fluid in the lung sufficient to create a curved shape that completely obscures the flat sides. But alveoli must be relatively dry to function. It may be that the fluid layer along the wall is not even continuous. An alveolus with the amount of fluid in it to accomplish such a spherical shape would be severely edematous, and that condition far exceeds the amount of fluid in a normal lung. Furthermore, it is an unstable condition. Once the fluid achieved a continuous curve its surface tension would draw in

more fluid and quickly fill the entire alveolus with fluid rather than cause it to collapse.

Moreover, the alveolar walls are penetrated by numerous interalveolar pores that, although some may contain fluid, can function to equalize the pressures in the lung and allow ventilation of alveoli with blocked airways. It is important to understand that, as long as either the airways or the aforementioned pores are patent, the pressure on either side of the alveolar surface is identical regardless of the size of the alveoli involved. The presence of these pores means simply that a pressure difference between alveoli is an unlikely condition. All of these features of the alveolus mean that, save for the minimal effect in the corners, Laplace's law has little relevance to the inflation, or resistance thereto, of an alveolus.

The surfactant properties of the fluid in the lung are important but need be considered neither perfect nor amazing. A generally neglected component of their function in terms of reduction of resistance to inflation lies in the small, distensible airways. As a lung is allowed to deflate, the small airways collapse before the alveoli, and gas is usually trapped in the distal portions of the tissue (4, 5). This observation was common enough when the respiratory "dog lab" was a regular part of a physiology course. For those deprived of that experience, you will have to trust me that an isolated lung does not collapse completely (nor will a piece of excised lung tissue), and to get all the air out of an excised intact lung, a vacuum must be applied to the bronchus.

The small airways lack the cartilaginous reinforcement of the larger airways and have a muscular wall. The wall is often complicated in its geometry by having a crenate margin (refer to the airway in Fig. 1) created by longitudinal folds in the mucosa. The patency of the small airways is effected by radial traction of the connective tissue matrix and resisted both by the muscles in the wall and by the surface tension on the curved surfaces, not just of the circular walls but of the fluid within the crenelated surface. It is on those surfaces that Laplace's law and surfactant come into play (3, 11).

The longitudinal folds make the airway highly compliant, because the folds allow the airway to alter its

circumference with little resistance. As long as the fluid lining the airway is principally confined to the space between the folds, the airway can change diameter with little regard to the surface tension of the fluid. When the diameter becomes small enough that the fluid forms a continuous surface above the folds, the surface tension becomes an important factor and results in an abrupt change in the relationship between the diameter of the airway and the pressure necessary to keep it patent. In this case, the airway is drawn closed, and a liquid bridge forms that closes the airway. This phenomenon also requires a substantial pressure in the airway to reopen it. This pressure is made much lower by the presence of surfactant and its reduction of the surface tension in the fluid closing the lumen. It should also be apparent that the presence of excess fluid in the lung makes it more likely that these small airways will close.

In summary, there is no question that some forms of Laplace's law and the properties of pulmonary surfactant are important for understanding the mechanics of the lung. However, the suggestion that alveolar mechanics is related at all to Laplace's law of elastic spheres is simply wrong. The opening and closing of the small airways account for many of the properties of whole lung mechanics that were once attributed to opening and closing of alveoli. It is time we understood that the Y-tube model of the alveolar inflation and the bunch-of-grapes model of alveolar anatomy deserve a place, not in our minds and textbooks, but in the museum of wrong ideas.

Address for reprints and other correspondence: H. D. Prange, Medical Science Program, Jordan Hall, Indiana University, 1001 E. 3d St., Bloomington, IN 47405 (E-mail: prange@indiana.edu).

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