REVIEW ARTICLE

The Law of Laplace and Its Relevance to Contemporary Medicine and Rehabilitation

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Objective: To show that the Law of Laplace is not only a historical curiosity but also remains relevant to our daily teaching and clinical activities.

Data Sources: Comprehensive MEDLINE (1960–2000) and CINAHL (1982–2000) computer literature searches performed by using key words such as *Law of Laplace*, *Laplace*, and *Laplace relationship*. Additional references were obtained from the bibliographies of the selected articles. Supplementary searches were also made by using various Internet search engines.

Study Selection: Primary references were used whenever possible.

Data Extraction: A single reviewer assessed all references and extracted information relevant to the Law of Laplace.

Data Synthesis: Although the Law of Laplace is attributed to Pierre Simon de Laplace, Laplace may not deserve the credit for the discovery. Nevertheless, the relationship (T [tension] α P [pressure] R [radius]) is easily derived and improves our understanding of the physiologic basis of many of our medical and rehabilitation practices. For example, the Law provides an insight into the mechanism of action of compression garments and lumbosacral orthoses, an understanding of the role of uterine muscle during delivery, and a reason why cesarean sections are made in the lower uterus. In addition, the Law explains many aspects of such diverse phenomena as penile erection, compartment syndromes, and peripheral edema. Perhaps most important, the Law explains the basis of many common medical practices that we use to promote bladder emptying, to control edema, and to plan surgery.

Conclusion: The Law of Laplace explains the mechanism of a wide range of physiologic phenomena. Unfortunately, even though it was developed about 200 years ago, the insights it provides us are often underused. More consideration of its implications can improve our clinical practice, our teaching, and our enjoyment of medicine.

Key Words: History; Laplace; Pressure; Rehabilitation; Tension.

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MOST OF US REMEMBER being exposed to the Law of Laplace in a physiology course and, with a little effort, associate it with the pulmonary system and alveolar function. Some of us remember that the Law associates the tension (T) in the walls of a container with its radius (R) and the pressure (P) of its contents. Very few of us, however, easily recall the nature of the relationship (T is proportional to the product P$\times$ R) or believe that it is pertinent to either our current practice or our understanding of medicine. This review is written to disabuse us of this idea and to show that this Law has a place in our everyday teaching and clinical activities.

Much of our difficulty in appreciating or understanding the Law lies in the dry and arcane way that it was first presented to us, which was 10 to 15 minutes in a respiratory physiology course in which the emphasis was devoted to the specifics of respiratory physiology and surfactant. No effort was devoted to its derivation, underlying assumptions, or to the insights it can give us in the functioning of many of the body's systems.

METHOD

Comprehensive MEDLINE (1960–2000) and CINAHL (1982–2000) computer literature searches were made by using key words such as *Law of Laplace*, *Laplace*, and *Laplace* relationship. Approximately 55 appropriate references were identified and retrieved with the assistance of our medical library. Additional references were obtained from the bibliographies of the selected articles. Supplementary searches were made by using various Internet search engines and medical textbooks. Primary references were used whenever possible.

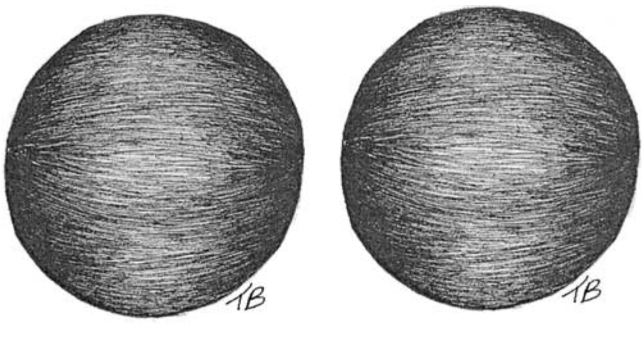
Historical Background

The derivation of the Law of Laplace is attributed to the noted French scientist and intellectual Pierre Simon de Laplace (1749–1827), who lived through the French Revolution and the rise and fall of Napoleon Bonaparte. Laplace was an interesting man who was not only an excellent scientist but was also politically astute. Thus, he not only worked with scientific luminaries of the time (eg, D'Alembet, Lavoisier) but also survived the executions of the Revolution and was even Minister of Interior Affairs (Attorney General) of France for a brief period.[1]

This attribution may be too simple. Laplace, in fact, may not deserve credit for the discovery of the relationship because many believe that one of the Bernoulli family had established the association almost 100 years earlier.[2] Others claim that a case can be made that Lagrange, Helmholtz, or other less well known scientists deserve the credit.[2,3] In any event, the eponym is firmly rooted, and I will use it in this article.

What Does the Law Mean?

Simply stated the Law of Laplace says that the tension in the walls of a container is dependent on both the pressure of the container's contents and its radius. The importance of the first of these terms is intuitive. If the pressure in a vessel is increased, we expect the wall tension to increase. Thus, if we double the pressure contained in a rigid container (whose



$T_o = P_o R_o$ $T = 2P_o R_o = 2\ T_o$

Fig 1. Pressure-wall tension relationship for rigid containers. If the pressure (P) contained in a rigid container (ie, whose radius [R] is fixed) is doubled, the tension (T) (force/unit area) in its walls also doubles.

radius is fixed, by definition), the tension (force/unit area) in its walls, as we would expect, also doubles (fig 1). Unfortunately, when we extend our consideration to a more physiologically reasonable nonrigid "container" such as the bladder, the situation becomes more complex. In this case, the walls of a container distend as the pressure increases and, in doing so, alter the pressure-volume-wall tension relationships of a rigid container.

Common sense still applies, however. The important fact is still that the walls of a container must direct a force inward to counterbalance the tendency of its contents to expand. However, the picture is more complicated than is the case for a rigid container because as the diameter of a nonrigid object is increased, its walls flatten and the force directed inward relative to the tension in its walls is less. As a result, a higher tension is necessary to contain the same pressure. Figure 2 can help clarify this. On the left side of this figure, a rubber band is being pulled around a cylindrical rod with a tension (T) and generates a strong inward force (F). However, on the right side of the figure, the band is straight. In the latter case, the band's forces are tangential to the surface of the cylinder and therefore exert no forces on it.

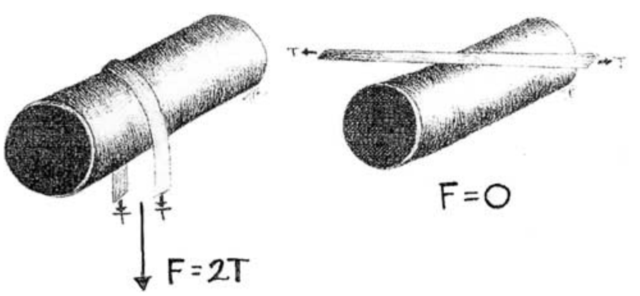


Fig 2. Demonstration of the relationship between radius and inward directed wall forces. On the left, a rubber band is being pulled around a small cylindrical rod with a tension (T) and produces a strong downward directed force (F). On the right side of the figure, however, the band is under the same tension, but because its forces are tangential to the cylinder (ie, similar to the situation that would occur with a cylinder with a very large radius), the downward force is 0.

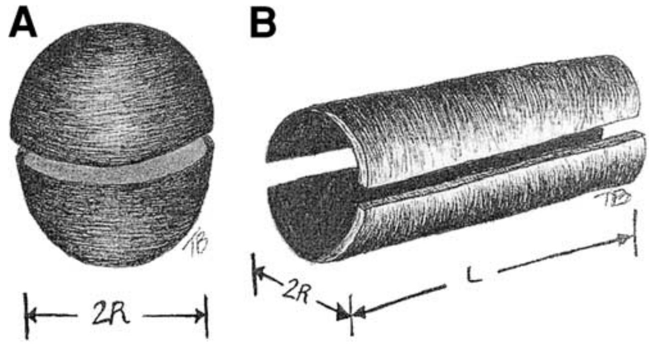


Fig 3. Derivation of the Law of Laplace for (A) hollow spheres with a radius (R) and (B) cylinders of length (L) and radius (R). Note that in the case of the cylinder, it is assumed that the length is much longer than the radius and that the circumference can be approximated with the quantity 2L.

Although the Law of Laplace seems esoteric, its derivation for the hollow spheres and cylinders that can serve as models for many organs is surprisingly simple.[4] First imagine the case of a spherical container, such as a balloon, filled with air (fig 3A) or a similarly filled cylinder cut from a longer tube (fig 3B). If the walls are to contain the air, the forces in them must counterbalance the outward force of the trapped air. In other words, $F_{wall} = F_{air}$.

Because the tension (T) in a wall is defined in terms of force per unit length, the total force exerted by the wall to contain the air is equal to the product of the tension in the walls of the container and its circumference. Thus, for a sphere and cylinder, respectively:

$$F_{wall} = T(2\pi R) \text{ Sphere}$$

$$F_{wall} = T(2L) \text{ Cylinder}$$

F_{air}, on the other hand, is the force exerted on the walls of the vessel by the pressure of its contents. The nonvertical components of these forces always have an equal and opposite counterpart. As a result, they cancel each other, and the net force the walls have to resist is equal to the product of the pressure within the container and its cross-sectional area (figs 3A, 3B). It follows then that:

$$F_{air} = P(\pi R^2) \text{ Sphere}$$

$$F_{air} = P(2RL) \text{ Cylinder}$$

Then, because the container is neither expanding nor contracting, the forces exerted by the walls are equal to those produced by its compressed contents. Therefore, $F_{wall} = F_{air}$, which for the cases of the sphere and cylinder that we are discussing reduce to:

Sphere	Cylinder
$F_{wall} = T(2\pi R) = P(\pi R^2) = F_{air}$	$F_{wall} = T(2L) = P(2RL) = F_{air}$
$T(2\pi R) = P(\pi R^2)$	$T(2RL) = P(2RL)$

These simplify to, respectively:

$$T = PR/2 \text{ (equation 1A) Sphere}$$

$$T = PR \text{ (equation 1B) Cylinder}$$

In actuality, the walls of a sphere or cylinder are not arbitrarily thin; they have some width. This can be accounted for if the tension is defined as force/unit area of the wall rather than as

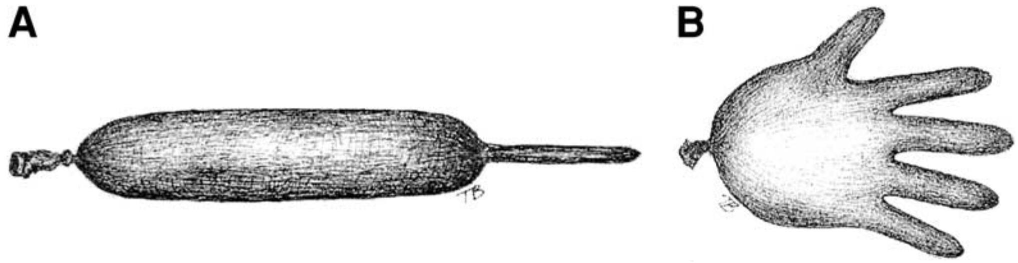


Fig 4. Implications of the Law of Laplace for (A) a long narrow balloon (the region of expansion spreads from an expanded region into the unexpanded portion) and (B) a surgeon's glove (the wider palm expands before the narrower fingers).

force/unit length. When this is done, the same expressions can be rewritten as:

$$T = PR/2w \text{ (equation 2A) Sphere}$$

$$T = PR/w \text{ (equation 2B) Cylinder}$$

where w is the wall thickness.

Cylinders and spheres are reasonable approximations for organs such as the blood vessels, colon, and bladder. However, before we consider applying the Law to these systems, it is interesting to see how Laplace's relation explains phenomena that we encounter in everyday life. For example, the Law explains why:

1. It is more difficult to begin blowing up a balloon than it is to continue inflating it up once the process has begun. (The reason is that it is easier for the wall of the balloon to resist expansion when it is minimally expanded and its radius is small than it is when the balloon is more fully inflated and the radius is larger [equations 1A, 1B]).
2. Once you begin blowing up a balloon, the pressure needed to continue filling it remains relatively constant until the material's elastic limit is reached. (This is similar to the concept of bladder compliance and again is the result of the properties discussed previously.)
3. In an elongated balloon, the region of expansion spreads from an expanded region into the unexpanded portion (equation 1B, fig 4A). (As earlier, it does not take as much wall tension at a small radius to resist expansion as it does in the area of the larger radius.)

Even though the equations explain these behaviors, the best way to understand them intuitively is to experiment with an assortment of variety store balloons. With the first balloon, you immediately discover that it is harder to begin blowing up a balloon than it is to continue filling it. A skinny elongated balloon, such as those twisted often into animal shapes, has such a small radius that it is almost impossible to inflate it without resorting to a pump. Perhaps the most interesting experiment of all is to inflate a balloon, to connect it to a small cylinder (eg, the cutoff barrel or container of a 12-mL syringe), and to attach an empty balloon to the other end (fig 5).[5] As you squeeze the larger balloon and force more air into its smaller counterpart, there comes a point when external force is no longer needed and the air remaining in the previously larger balloon spontaneously flows into the second balloon. Finally, blowing up a surgical glove shows the preferential expansion of the large diameter palm area over the smaller radii fingers (fig 4B).[6]

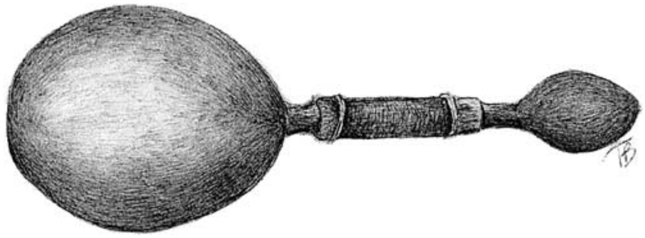


Fig 5. If 2 balloons of different diameters are connected by a hollow cylinder, the smaller spontaneously empties into the larger.

I hope I have managed to show that, even with balloons, the Law of Laplace is not just a dry, technical exercise. In fact, because it gives the relationship between the tension (ie, the force tearing them apart) in the walls of a container and the pressure that it contains, it has direct ramifications for organs such as the bowels and bladder as well as pathologies such as aneurysms. I will review some of these physiologically interesting and important situations in the next few sections.

PHYSIOLOGIC APPLICATIONS TO REHABILITATION MEDICINE

Bladder Function

Bladder function is an important aspect of rehabilitation. The Law of Laplace gives us several insights into bladder distension. First, one should remember that the larger the volume of a filled bladder, the larger its radius and the greater its wall tension (equation 1A). This tells us a few things that are clinically important. For example, the wall tension (and the possibility of tissue injury) is far higher in a distended bladder (especially at its widest portion) than would be the case for a less-filled bladder at the same pressure. In addition, the same volume-pressure relationship tells us that it is easier for the bladder wall to produce the pressure necessary to initiate and maintain a stream of urine when the bladder is smaller than when it is more fully expanded. The Law of Laplace, thus, provides a mechanical rationale of why keeping a bladder's maximum volumes below 400 to 500mL protects it from damage and promotes return of function.[3,7,8]

Although the Law of Laplace is useful, it is important to remember that it is an approximation. What actually happens is more complex. In the early stages of filling, the bladder is essentially unfolding from a collapsed state and the Law is not applicable. In later stages, even when the bladder is distended, elastic effects are important, but viscoelastic properties, smooth muscle contractions, and neurologic responses may become more important.[7] Nevertheless, the relationships between bladder volume, wall tension, and pressure described by the Law of Laplace are, at least, heuristically useful.

Peripheral Edema

Compressive wraps and garments are frequently used to treat peripheral edema that is refractory to medication and dietary changes.[9] Here again, a simple look at the Law of Laplace gives one insight into a number of clinical observations and practices. Two of these—(1) that it is easier to keep edema from forming than it is to reduce its volume once it is present and (2) that slender people seem to do better with stockings than their heavier counterparts—follow from the proportionality between the tension in the wrap or stocking and the product of pressure and radius described by the Law. In particular, for a given stocking fabric tension, the pressure exerted on the tissues of a limb is less for large diameter limbs than it is for those that are less swollen (equation 1B). This fact supports the clinical practice of telling people with edema to don their stockings immediately on getting up in the morning. In addition, it explains the observation that stocking success, whether in controlling edema or in supporting blood pressure in those with orthostatism, is more common in slender people than it is in the obese or those in which edema reduction was only partially successful.

The Law also explains why compression stockings are often uncomfortable at sites with sudden changes in radius such as the ankle and at skin folds. The reason is that the concentration of pressure over localized areas with a prominence (ie, having small a radius) will be inordinately high (equation 1B, fig 2A).[3] At times, however, this concentration may be used to advantage. For example, narrow cylinders of soft cotton placed under compression stockings and over the sclerosed veins of people who have undergone sclerotherapy increase the pressures on these veins by a factor of 2 or more and assist in maintaining their closure during healing.[10]

Lifting and Abdominal Supports

The benefit of lumbar and abdominal supports in the treatment and prevention of low back pain is controversial. Nevertheless, it is instructive to look at the anatomy of the region and what the Law of Laplace may tell us. First, the abdominal cavity can be considered as a container filled with a relatively incompressible fluid.[3] The walls of this container are formed by the pelvis, the diaphragm, the spine and paraspinal muscles, and the abdominal musculature (obliques, rectus abdominus). Because more than half of these (the diaphragm and abdominal musculature) can be considered elastic, the Laplace relation should be applicable. Assuming applicability, a number of things become obvious. First, obese or pregnant people have abdomens with large girths and hence the abdomen requires much higher wall tension (muscle stress) than would be necessary in a more slender person if the person with large girth were to support a lifting maneuver by increasing the pressure within their abdominal cavity (equation 1A). Similarly, a binder on a slender person would be expected to produce a higher pressure on the abdominal contents for a given tension than would occur in the case of a more obese counterpart.

MEDICAL AND SURGICAL IMPLICATIONS OF THE LAW OF LAPLACE

Heart Failure

The Law of Laplace describes the behavior of thin-walled elastic containers. (In fact, on a strict basis, its validity is limited to situations in which the wall thickness/cavity diameter ratio [w/d] is less than 0.1.[11,12]) The heart, of course, has thick walls. Nevertheless, Laplace's relationship can still give us insight into its behavior. On the most obvious level, the tension in a chamber's walls increases (equation 2A) during systole as the pressure increases. In addition, a larger ventricular diameter, such as occurs in congestive heart failure, leads to higher wall tensions than would occur in a normal heart with a smaller chamber radius (equation 2A). The width of the wall (w) also comes into play: as the heart hypertrophies in response to failure, the thickening of its walls tends to reduce the tension (F/A) within them (equation 2A). The opposite also occurs; narrowing of a heart's wall thickness, such as may occur after a myocardial infraction, leads to higher localized wall tensions and an increased risk of further stretching.

Laplace's Law, thus, provides a rationale for the heart's differing responses throughout the stages of heart failure.[13] For example, the earliest stages of failure are marked by hypertrophic wall thickening (ie, an increased w in equation 2A) and a lowering of wall tensions. However, once failure progresses and the ventricular diameter increases, wall tensions increase (equation 2A) and compensation becomes more difficult.[14] This application of the Laplace relation is helpful but simplistic. In life, as failure progresses, ejection becomes less complete, and wall tensions remain elevated throughout the cardiac cycle. As a result, coronary perfusion is impaired and contributes to an accelerated deterioration.[13,14]

Hypertension

Peripheral resistance produced by vasoconstriction of arteriolar vessels with diameters less than half a millimeter is important in the genesis of hypertension. The cylindrical form of Laplace's relation provides some insight into how these tiny vessels can maintain their constriction in the face of the increased pressures they must contain (equation 2B, fig 3B).[15] Thus, according to equation 2B, the small radius of the constricted vessels permits large pressures to be resisted with relatively low wall stresses. With time, the wall thicknesses increase[15] and reduce wall tensions by spreading the forces over larger cross-sectional areas (equation 2B).

Pulmonary Physiology

I noted earlier that if 2 balloons were connected, the smaller would spontaneously empty into the larger (fig 5). The pulmonary system would seem to contradict this idea in that this reasoning would predict that smaller alveoli would progressively empty into larger alveoli that, in turn, would subsequently empty into even larger ones.[16] The logical conclusion would be that the lung would ultimately consist of a single sack. This obviously does not happen.

The reason that this does not occur is not because of the failure of the Law of Laplace but because of a failure of a model of the alveoli as simple grape-like sacks with elastic walls. The complicating factor is that the alveoli are coated with a material (surfactant) that has the property of having a surface tension that lessens as alveoli walls contract and increase its concentration.[16] In fact, as an alveolus contracts, the concentration of surfactant, and hence its effectiveness in reducing surface tension, increases in a manner that balances the increasing pressures generated by its walls on the air it contains. In effect, the effects of the surfactant and wall tension cancel each other and permit our lungs to function in the manner that they do.

Esophageal Varices

The risk of esophageal variceal bleeding increases as the diameter of the variceal increases.[17] Because the esophagus is a tube, it seems reasonable that the cylindrical form of Law of Laplace (equation 2B) might be applicable to it and its varices. Until recently, this thought was just speculation. However, advances in ultrasonic imaging and pressure monitoring show that the Law can provide a good approximation of the relationship of variceal diameter, wall thickness, and tension.[17]

Table 1: Additional Medical Applications of the Law of Laplace

Condition	Application	Insights from the Law of Laplace
Spinal cord injury[20]	A model of the spinal cord as a tube with the meninges surrounding a semisolid parenchyma	Injuries that occur with moderate spinal cord distraction (eg, during scoliosis surgery) may be because of intrinsic pressure and rather than trauma
Penile function[21]	Penile erections can be modeled as an elastic cylinder with the tunica albuginea surrounding the cavernous space	Improved understanding of relative role of hydrostatics and hydrodynamics in erections
Vascular aneurysms[22]	Investigation of the biomechanics of aneurysms	Rationale for the findings that the highest wall stresses occur at the sites of largest circumference and smallest thickness
Intramuscular forces[23]	Muscles modeled as elastic thin walled containers	Improved appreciation of the effects of swelling in muscle function and fatigue
Bladder obstruction[8]	Bladder compliance	Clarification of the relationship of filling volume and wall compliance
Urinary reservoirs and bladder augmentation[8]	Stress and pressures in the walls of surgically developed reservoirs	The larger the diameter of the reservoir, the higher the forces on its anastomoses
Pulmonary edema[24]	Alveolar pressure are constant in experimental models of pulmonary edema	Alveoli fill in an all or none manner in pulmonary edema
Ocular explosion[25]	Ocular ruptures as the result of inadvertent injection of periocular anesthetics into the globe of the eye	The Law can explain the basics of ocular rupture
Glaucoma[26]	Myopic people (who have larger, thinner-walled eyes than those with normal vision) have higher rates of glaucoma	The Law predicts that myoptics would have high wall tensions and thus that glaucoma's effects may be because of wall stress as well as intraocular pressure itself

Pregnancy

The Law of Laplace is also applicable to obstetrics and pregnancy. For example, pressures are the same throughout a container. In the case of the gravid uterus, this means that wall tensions are greater in its fundus than in its narrower pelvic portion (equation 1A). Because the tension in a wall is really a measure of the forces tearing it apart, this difference adds biophysical support to the practice of performing cesarean sections in the smaller diameter, lower wall tension, lower uterus.[18] In addition, although we have been simplifying things by assuming that the external pressures around a container are zero (eg, fig 3A), what is really important is the transmural pressure—the difference in pressures across the wall of the container. With this in mind, a number of additional aspects of pregnancy, labor, and delivery become clearer. For example, bearing down during delivery results in lower uterine transmural pressures, an effective reduction in the pressure of the uterus, and therefore less stress on its walls (equation 1A). In addition, as labor progresses and the uterus becomes smaller because of the loss of amniotic fluid and progression of the delivery, the stress in its walls necessary to maintain the same pressure lessens (equation 1A). This, in turn, makes it easier to maintain or increase the forces that are necessary to stretch the birth canal, a process that requires still less force as the diameter of the canal increases.[18]

Abdominoscrotal Hydrocele

Abdominoscrotal hydroceles, although rare, offer another interesting example of the implications of the tension-pressure relationships described by the Law of Laplace. These hydroceles begin with a scrotal component and a narrow inguinal portion whose expansion is limited by the myofascial tissue that surrounds it and prevents its migration proximally.[19] However, as the scrotal portion grows, its walls are stretched and the pressure within them increases (equation 1A). However, the peritoneal cavity is an area of low pressure (2–6.5cm of water),[19] and as the pressure in the scrotal hydrocele becomes higher than the intraperitoneal pressure, there is a tendency for the formation of an intraperitoneal component that ultimately may grow in a manner similar to that of the connected balloons of figure 5. Hydrocele volumes of 1.3L have been reported.[19]

ADDITIONAL APPLICATIONS OF THE LAW OF LAPLACE

The Law of Laplace describes an amazing number of physiologic phenomena. We have discussed several applications that seem particularly pertinent or striking. Many more exist. Table 1 lists additional situations in which the Law of Laplace can give us an improved understanding of the body and the functions of organs ranging from the eyes to the muscles and spinal cord.

CONCLUSIONS

The Law of Laplace can furnish us with an improved understanding of the functioning of the body and the practice of medicine. Nevertheless, it provides a mechanistic view that may not take into account the adaptations that may occur in a living organism. As a result, a number of caveats need to be kept in mind. The first of these has already been made several times—the body is capable of adapting and changing its behavior in response to stress (eg, wall hypertrophy, the response of the nervous system). In these situations, the Law may not apply or may need to be applied in a way that accounts for these changes. The second caveat is that the model may be too simple or that all the important characteristics of the organ being studied are not being considered. We have already seen an example of this in the pulmonary system: the Law predicts that multiple alveoli are not possible until surfactant is included in the calculations. Other physiologic processes may also be important. Among these are that an organ's walls may not be uniform and that the assumptions of the Law break down when a tissue's elastic limits are reached. Finally, it is important not to expand, at least without considering the effects of doing so, the Law beyond its limits of applicability. In particular, the thin wall ($w/d<0.1$) restrictions[11,12] must be kept in mind. Even with these limitations, the Law of Laplace helps us understand a wide range of physiologic and pathophysiologic processes.

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