Principles of Physics in Surgery: The Laws of Mechanics and Vectors Physics for Surgeons—Part 2

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Abstract In this sequel, to an earlier article, we discuss the laws of Mechanics, Thermodynamics and Vectors as they apply to soft and bony tissues. These include the Laplace's Law as applied to colonic perforation, compression therapy, parturition, variceal rupture, disc herniations etc. The Pascal's Law finds use in hernia repair and the Heimlich maneuver. Trigonometrically derived components of forces, acting after suturing, show ways to reduce cut-through; the thickness and the bite of suture determines the extent of tissue reaction. The heating effect of current explains the optimum gap between the prongs of a bipolar cautery and the use of law of transfer of heat in determining relation between healthy wound healing and ambient temperature.

Keywords Mechanics · Laplace · Pascal · Vectors · Suturing · Thermodynamics · Newton · Cautery

Introduction

“The Important thing is to never stop questioning.”
Albert Einstein.

The basic mechanisms of operation of living and non living things in nature are guided by laws of pure sciences i.e. Physics, Chemistry and Mathematics. In this article we analyze some of the basic laws of physics which form the understanding of the various pathophysiological mechanisms in various disciplines of medicine and guide some simple surgical techniques.

Aim

The present review article is an educational article illustrating the application of laws of mechanics, thermodynamics and vectors to soft and bony tissues of the body.

Material and Methods

The application of various laws was considered after discussion with various experts in the field of Biomedical engineering and biophysics and the most important principles which were relevant to clinical surgery were considered.

A systematic Medline search (1960–2008) was carried out using keywords such as Mechanics, Laplace's Law, Pascal's Law, Laws of Vectors, Suturing techniques etc. Additional references were obtained from the bibliographies of the selected articles.

Before, we begin with applications of individual laws to be dealt with in this article.

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In the Part I of this series on “Physics for Surgeons” we described the laws of flow dynamics. Due to paucity of space we limited the examples and clinical uses. We would like to illustrate some more examples:

Poiseuille’s Law

1. Nasogastric aspiration in Intestinal obstruction- A wide bore Ryle’s tube—FG-18 or 20 (large diameter- bigger r) should be inserted to and connected to a large diameter tubing of UROBAG, and not to a narrow tip of a I.V.dripset with a long tubing. A wider Ryle’s tube with a short and wide tube of urobag will increase the flow rate (more r , less l).
2. Vacuum Suction drain: One should use a wide bore—FG 16 or 14 size drains and connect it directly to the receptacle tubing without the T piece nipple end. The narrow T nipple offers a site of constriction and blocks the free flow of blood; as a result the clot forms and blocks the tubing. The vacuum chamber should be collapsed fully on the day of operation (to keep the Δp high) and next day till the bleeding continues (RBC settling down on the bottom side of drain tube). When you see the RBC settled on the tube with clear translucent serum above, you know that the active bleeding has stopped and it is mostly serum or lymph that is draining. When this happens, you should reduce the vacuum in the drain receptacle so as to minimize the pressure gradient between the operated site and the container receptacle i.e. less Δp , this will reduce the rate of fluid drainage and allow early removal of drain. This latter point has been well demonstrated in a 2005 RCT study, comparing half versus full vacuum suction drainage after modified radical mastectomy for breast cancer, which showed significant reduction in the total hospital stay of patients on half vacuum suction drainage systems as compared to those on full suction drainage without any added morbidity (like incidence of seroma) [1].

3. Repair of a hollow tubular organ viz. intestine, bile duct, ureters, vas deference, fallopian tube, blood vessel etc. Since the flow rate is radius raised to the power four ($Q = \Delta p \pi r^4 / 8 \eta l$), it behoves on the surgeon to be cognizant of this equation while repairing these tubes and keep the anastomosis as wide as possible.

Applications of Individual Laws

La Place’s Law [2]

It describes the relationship between the transmural pressure difference (P) and the tension (T), radius (r), and thickness of the vessel wall (M) (Fig. 1). This law can be expressed in the following algebraic equation:

$$\text{Transmural Pressure difference} = \frac{\text{Tension} \times \text{Mural Thickness}}{\text{Radius}}$$

Or

$$P = \frac{T \times M}{r}$$

Thus higher the pressure difference the more the tension on the walls, the larger the radius the more the tension but on the other hand, the thicker the wall the lesser the tension.

For spherical organs: like stomach, urinary bladder, and uterus. $P \propto 2 T/r$

For cylindrical organs: like intestine, blood vessels and ureters. $P \propto T/r$

La Place’s law can be applied to explain the following clinically observed phenomena:

1. Variceal wall tension—With increased radius there is increased tension .With decreased wall thickness there is increased tension. So when elastic limit is reached, a

Fig. 1 Demonstrating Laplace’s Law for cylindrical and spherical organs

small change in volume (or radius) is associated with a large increase in tension. Once expansive pressure is greater than the tension that can be generated in the wall of the vessel, the varix will rupture. This is why larger a varix higher is the risk of rupture.

Similarly, in Marfan syndrome, the abnormality in the *fibrillin* [3] gene leads to abnormally weak and thin aortic wall leading to increased radius at normal blood pressures and thus increased tension on the wall which further thins the wall and increases the tension on the wall (a vicious cycle). This accounts for the well-documented increasing risk of dissection and aneurysms as the aortic root caliber increases [3].

2. Lumbar Disc Herniation—The cylindrical shape of the lumbar disc and its high water content in young persons allows the application of La Place's law to study its mechanics. Normally a lumbar intervertebral disc is flattened antero-posteriorly which means the radius of curvature of the posterior surface of the disc is very high. According to the Laplace's Law this would cause a very small amount of outward pressure to be exerted on the posterior annulus fibrosus. However due to degenerative processes when the disc becomes weaker it could develop a more rounded shape thus leading to a reduction in the radius of curvature particularly of the posterior surface. The slightest decrease in the radius will cause greater outward pressure to be exerted at this minor bulge ($P=T/R$) leading to a greater bulge and further reducing the radius of curvature. This process once begun will be progressive until the annulus fibrosus loses integrity and the nucleus pulposus herniates.[4]
3. Compression Therapy of edematous limb [5]—Applying a compression bandage on an edematous leg is an effective way to reduce the swelling. According to the Laplace's Law, the compressive pressure that will be generated on the bandaged limb will vary directly with the tension used to wrap the bandage and inversely with the existent diameter of the leg ($P=T/R$). This pressure is transmitted to the veins which get compressed thus increasing the venous return of the limb. A similar effect also increases the lymphatic flow out of the limb. Of added benefit is the fact that the diameter of the leg increases progressively from the ankle upwards. So, if the same level of tension is applied while bandaging the leg it would follow from Laplace's Law that there would be a fairly uniform pressure gradient along the leg: highest at the ankle and the least at the upper thigh.

However, with gradual reduction in the diameter of the limb higher pressures get exerted on the vessels. This must be kept in mind when tying subsequent bandages, as applying the same amount of tension on

the bandage after some reduction in the swelling has occurred might raise the compressive pressures on the vessels, particularly on the lymphatics, so high that they might collapse. This will nullify the reduction in limb swelling made earlier.

Limb Bandaging—While bandaging a limb, if the bandage is distorted around a bony prominence, there will be higher pressure exerted around the particular point (as the tension will be the same throughout the bandage). The sharper the curvature greater will be the local pressure and hence chances of pressure necrosis. Flattening out this curvature with soft padding will make the radius of curvature more uniform around the limb. However too much padding can make matters worse by itself creating a sharper bump. [6] (Fig. 2a–c).

4. Bladder Reconstruction—In selection of intestinal segments for bladder substitution detubularized bowel (i.e. more spherical and as $P=2T/r$ for a sphere whereas it is $P=T/r$ for a cylinder) segments provide greater capacity at lower pressure and require a shorter length of intestine than do intact segments. They accommodate to filling more readily because, the container with the greater radius will develop less pressure and thus hold larger volumes at lower pressure [7].
5. Placental Haemostasis—Haemostasis from the placental bed is due to compression of the uterine vessels as they pass through the myometrium. The degree of compression of these vessels depends on the force acting on the vessels. This force obeys the Young-Laplace relationship ($F=2 T/r$), where F equals the compressive force acting on the blood vessels, T is the wall tension (generated by the uterine contraction), and r is the radius of the uterus. It is apparent that the force compressing the vessels cannot be very high if r is large. Therefore, it is essential that the radius of the uterus be made small by emptying the uterus of any blood clot or placental tissue. The wall tension (T) of the uterus is increased by giving oxytocics. This is the scientific basis of the initial treatment and the prevention of primary postpartum haemorrhage [8].
6. Dilated Cardiomyopathy—The heart becomes greatly distended and the radius (r) of ventricle increases. Therefore to create the same pressure (P) during ejection of the blood much larger wall tension (T) has to be developed by the cardiac muscle. The dilated heart requires more energy to pump the same amount of blood as compared to the heart of normal size. As a logical extension of the same principle, partial left ventriculectomy can be performed to treat end-stage heart disease that aims to reduce the ventricular radius [9].

Fig. 2 Depicting effects and applications of the Laplace's Law

7. Perforation of Caecum—Colonic distension due to distal obstruction usually results in perforation of the caecum and not the other portions of the colon. This is because the caecum has the greatest diameter in the larger bowel; hence it is exposed to the maximum distending tension, although the distending pressure is similar throughout the colon (in accordance with the [Pascal's law](#), see later) (Fig. 2a).
8. Artificial Rupture of Membranes—Releasing a significant volume of amniotic fluid permits enough reduction in the radius of the gravid uterus so as to generate enough tension to begin parturition and expedite labor [10].

At the dawn of the 19th century, M. Laplace presented his theory of capillary attraction to the Institute of France, in which his law relating wall tension of thin-walled sphere or tube to radius and cavity pressure first appeared. Nearly two centuries later, this law appears to have found its most

direct application in a novel surgical therapy for congestive heart failure, called ventriculectomy. As described in this issue, Bellotti et al 1 report on cardiac chamber mechanics in 11 patients with severe dilated cardiomyopathy (DCM), before and after partial removal of a portion of their ventricular wall. This is not performed as a means of aneurysm resection, since the excised wall behaves no differently from any other portion of the chamber left behind. Rather, this procedure aims at directly reversing a degree of chronic chamber remodeling and dilation associated with DCM. Since chamber volumes are reduced without acute changes in wall thickness or cavity pressure, wall tension is diminished. Furthermore, if cardiac output is maintained, then by ejecting from a smaller starting (diastolic) volume, both fractional shortening and ejection fraction will increase. Chamber volumes are also inversely related to E_{max} , an index of chamber contractility, so that this index might also increase after ventriculectomy. All these changes were indeed observed by Bellotti et al.

Pascal's Law

Given by Blaise Pascal in 1652 states [11] that “pressure applied to a confined fluid at any point is transmitted undiminished throughout the fluid in all directions and acts upon every part of the confining vessel at right angles to its interior surfaces and equally upon equal areas” (Fig. 3). It finds application in the following clinical situations:

1. **Intrauterine pressure Measurement**—It is obtained via an open-end, fluid-filled intrauterine pressure catheter attached to an external strain gauge transducer. Presuming that intrauterine and intracatheter fluid to be part of a closed system, Pascal's law provides that the intrauterine pressure generated by a contraction will be transmitted directly to the pressure transducer.
2. **Prosthetic Hernioplasty**—To illustrate the principle of hernia repair, we can imagine a bathtub (Fig. 4). When a rubber stopper is placed at the outlet from inside the tub and the tub is filled with water, the water pressure pushes the stopper in place and keeps it fixed there. The more the water pressure, the more firmly does the stopper gets applied.

On the other hand, if we were to put the stopper from outside the water pressure is going to push the stopper out as the pressure increases.

Fig. 3 Showing the Pascal's Law

Fig. 4 Example showing Pascal's law as a basis for Inlay mesh repair Hernioplasty

The same scenario can be imagined while placing a prosthetic mesh on the hernial defect. Application of mesh from inside as inlay gets firmly fixed as the intra-abdominal pressure rises. Onlay mesh repair on the other hand, is likely to result in recurrence of hernia if excessive rise in abdominal pressure takes place.

3. **The Heimlich maneuver**—Any pressure applied in the airway against the closed thoracic cavity sealed accidentally by the food particle is transmitted equally to the trachea as to the rest of the lung. If the constricting pressure (applied by the person performing the maneuver) generated in the thorax during the maneuver is large enough, the particle lodged in the trachea is pushed out relieving the choking. This is very similar to pushing out tooth paste by squeezing the tube.

Suturing Techniques and Laws of Vector

1. Factors determining 'Thickness' and 'Bite size' (i.e. length of the suture used) of the suture: The foreign body reaction to suture material is directly proportional to the volume of the implanted thread that varies as the first power of length but second power of radius.

$$V = \pi r^2 L$$

Where, V =volume, r =radius, and L =length of suture material.

Therefore to minimize the tissue reaction, the thinnest possible suture material with minimum possible length should be used. However as a caveat, fine threads cause more 'cheese-through' or cut-through as shown by Prof. HAF Dudley [12].

As shown in Fig. 5a, in technique A, with a thick bite of the linea alba, 'L' is large hence F_a is reduced and the tendency to cut-through is less compared to the technique B where double layered suturing is used. Here, width of the bites 'L₁' and 'L₂' are both small and so F_a is higher and moreover in the technique A, a suture of wider radius is used than in technique B. Hence this will also contribute to the less cut through force in technique A as compared to technique B.

Hence larger the tissue bite and thicker the suture, lesser would be the cut-through force. Thus, although a smaller radius and length of suture material will decrease the tissue reaction, it would also be deleterious in the form of increased cut-through force by the first power of radius and length. Thus thickness of tissue bites and thickness of suture needs to be carefully balanced.

2. Factors determining the 'Direction' of suture placement (acc. to Vector of force (F)): The Fig. 5b illustrates horizontal and vertical component vectors of force (F) acting along the placed suture are shown.

If, $\theta = 45$ degrees $\cos\theta = 0.7$. So, the cut-through force, i.e. $F\cos\theta$ is 0.7 F. This means a reduction to

two-thirds of the original force. Thus obliquely placed suture causes less cut-through force than the conventional transversely placed suture. But obliquely placed sutures increase the formation of dog ears when compared to conventional transversely placed sutures (if sutures are not given properly) due to increased vertical component of the force along the margins of the wound given by $F\sin\theta$.

The Fig. 5c shows the components of force after suturing of two incision wounds one big and the other small, placed in close proximity. In case of 2 parallel suture lines the forces of the 2 wounds get added and there is a high risk of wound breakdown. In the second example where the two wounds are aligned at right angles to each other the forces do not add up since the component of a force in the sutured small wound along the direction of the suture of the large wound is $F\cos 90$. Since $\cos 90 = 0$, the resultant of a force at its right angle is zero.

So to prevent delayed wound healing and possible cut-through, it is beneficial to make the line of incision of a second wound besides a larger wound, perpendicular and not parallel to the line of incision of the larger wound.

Fig. 5 Application of Vectors to Suturing techniques

Heat Produced by an Electric Current [13]

It is given by:

$$H = I^2 R t$$

Where: I=current; R=resistance; t=time

Accordingly, the heat generated while using a bipolar cautery is directly proportional to the resistance offered by the intervening tissue being cauterized. Too little a tissue thickness offers less resistance and hence less heating. On the contrary too much tissue offers so much resistance that the current flow stops for the voltage selected. Therefore for the particular voltage selected the thickness of the tissue being cauterized has to be of optimum thickness.

Hence it is advisable to keep the prongs of the cautery clean so as to let the optimum amount of current flow through them in order to produce the desired amount of heating.

Newton's Law of Cooling

The Newton's law of cooling [14] is given by the following formula:

$$\frac{dQ}{dt} = h \times A \times (T_{env} - T)$$

Where,

Q	Thermal energy
h	Heat transfer coefficient
A	Surface area across which the heat is being transferred
T	Temperature of the object's surface
$T_{(env)}$	Temperature of the environment

Newton's law of cooling can be applied to explain the following:

1. Effects on wound healing: Any breach in the continuity of a covering surface (skin or mucosa) is called a wound. Wound healing is influenced by many factors and one of the important factors is the ambient temperature [15] around the wound. The closer the wound temperature to the core body temperature the better is the healing. The rationale behind this is that during the early stages of wound healing the higher temperature helps macrophages in their phagocytic actions and is also inhibitory to the growth of the microbes. During the later stages of the healing various cells like epithelial cells, smooth muscle cells and endothelial cells continually divide to replace the damaged cells and fill up the gap of the wound and this mitotic activity is greatly enhanced by the raised temperature. Hence to raise the ambient temperature,

following strategies can be utilized in accordance with Newton's law of cooling:

- a. Dressing a large wound increases wound healing by preventing the loss of heat by evaporation (by decreasing the exposed surface area) and thus maintaining the warm ambient temperature of the wound close to core body temperature. For the same reasons hot fomentation also increases wound healing.
- b. Keeping the wound moist [16] also increases wound healing by decreasing the rate of heat loss by forming a thin film over the wound surface (thus decreasing the Heat transfer quotient)

Thus wound healing occurs optimally when the wound is kept 'moist' and 'warm'. Thus using an occlusive dressing like hydrocolloid dressing causes the temperature values to increase slightly, promoting the healing process [16].

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