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EDITORIAL

Basic Physics Revisited for a Surgeon

JS Rajkumar[1] · Pradeep Chopra[1] · Chintamani[1]

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> If you can't explain it simply, you don't understand it well enough.
> Albert Einstein

Virtually, every act around us, from the falling of an apple to a human falling in love, is explicable in terms of the basic laws of physics and chemistry that govern the running of the universe. Gravitational physics (apple) and hormonal neurochemistry (love) aside, it behooves every surgeon to have a basic understanding of these laws in order to have a three-dimensional view of surgery as not just an art but also as a precision science. It is from science, or how things work, that technology, or how to get things to work, emerges. These laws are not new to the surgeon but he barely makes a conscious effort to apply them. Often they are learnt during the preparation for exams and promptly forgotten soon after. The modern day surgeon has a dazzling set of tools and consequently it is one's duty to understand the fundamental basis of the functioning of these instruments and tissues that are operated on, which will make one appreciate the nuances of the surgical sciences. These secure modern-day instruments are as safe or hazardous as the person who is using them. For, "A fool with a tool is still a fool".[1] The understanding of these laws and their application would make a surgeon think more like a scientist. Before the days of John Hunter, who in Eighteenth century presented his research on popliteal artery aneurysm, the general perception about surgeons amongst physicians and other scientists was that of "able bodied and weak minded barbers". An effort has therefore been made to elucidate on these issues by taking up few basic laws of physics to explain as to how they can be applied to get better surgical outcomes.

✉ Chintamani
drchintamani7@gmail.com

1 Vardhman Mahavir Medical College, Safdarjang Hospital, New Delhi, India

Poiseuille's Law

It relates to the rate (Q) of blood flow through a blood vessel with the difference in blood pressure at the two ends ($\Delta P = P1 - P2$), the radius (r) and the length (L) of the artery, and the viscosity (η) of the blood [1].

$$\text{Volume flow rate} = \frac{\pi\ (\text{pressure difference})\ (\text{radius})^4}{8\ (\text{viscosity})\ (\text{length})}$$

This law can be expressed in the following algebraic equation: $Q = \pi\ r4\ \Delta P\ /\ 8L\eta$

Actually, this law is a lot less complicated than it appears at first glance. An increase in the diameter of a vessel from 1 to 2 mm will increase the flow rate by 16 times (for r=2, r4=16) if other factors shown above remain constant [2].

Today's surgeon applies Poiseuille's law in the following situations:

[1] Brady Booch.

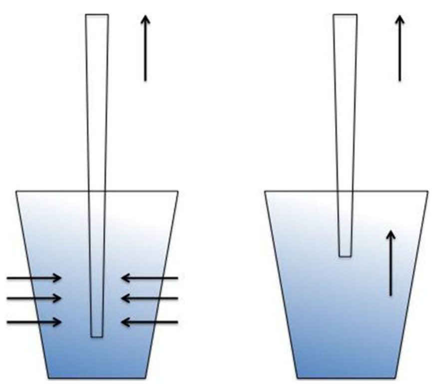
Gastroesophageal Reflux Disease

In surgical management of gastroesophageal reflux disease, the following steps are performed:

1. The herniated stomach (if there is a hiatus hernia) is brought back into the abdomen. The lower esophagus along with the esophagogastric junction is dissected from the posterior mediastinal areolar tissue, in order to have a length of lower esophagus lying free intra-abdominally.
2. The crural hiatus is narrowed by suturing (with or without mesh) the right crus to the left crus of the diaphragm.
3. The mobilized fundus of the stomach is pulled through the retroesophageal space to the right side of esophagus and sutured anteriorly. A circumferential 360° fundoplication is achieved thereby, which slightly narrows the radius of the esophageal-gastric junction.

In the first step described above, lengthening of the esophagus increases the *L* factor in the numerator part of the Poiseuille's equation, and, more importantly, crural suturing and fundoplication decrease the radius of the esophagogastric junction marginally but have an increased effect on the resistance by a factor of 4 ($r4$). The overall effect of these maneuvers increases the resistance at the lower esophagus and prevent excessive reflux across the esophageal-gastric junction.

This set of maneuvers is best explained by the soft straw experiment (please see figure).



A soft straw dipped into a glass of water will collapse on itself when sucked. This is because the hydrostatic pressure of the fluid compresses the straw from all directions. In this situation, the only way to make the straw functional is to pull back the straw so that only a short length of it is below the water. Now, the hydrostatic pressure, which acts upon the short length of the straw below the surface of the water, is inadequate to collapse it and the atmospheric pressure on the surface of the water pushes up the water in the straw.

Applying this principle in gastroesophageal disease, the starting point where there is gastroesophageal reflux is the end point of the experiment mentioned above. The completed fundoplication procedure represents the starting point of the straw experiment where the hydrostatic pressure collapses the straw. In effect, by lengthening the intra-abdominal esophagus, the surgeon permits the intra-abdominal pressure (similar to hydrostatic pressure) to compress the lower esophagus and increase its intraluminal pressure, thereby preventing reflux. Additionally, the fundoplication decreases the radius and increases the resistance, which further acts as an anti-reflux barrier.

It goes without saying that ignoring these vital factors is one of the main reasons for a failed anti-reflux surgery.

Tubes and Drains

1. For decompressing the stomach, a wide nasogastric tube connected to a short and wide tubing (e.g., urobag) will increase the flow by virtue of increased radius (r) and short length (L).
2. Good postoperative care is as important as the preoperative preparation and the operative technique, for a successful outcome of an operation. A nonfunctioning drain compromises many a time the result of a complex surgery. Using drains of a large diameter 16 or 18 F connected to short and wide tubing can increase the flow rate. Additionally, by applying vacuum, the ($\Delta P = P1 - P2$) is kept high. Normally, a universal connector is used to connect the tubing to the vacuum receptacle, which fits tubing of all sizes. This has a narrow nipple with a small (r), which decreases the flow, clotting of blood and failure of the drain. Use of a wide connector will prevent this [2].
3. The downside of excessive negative pressure suction is continued effluent from the drainage tube. This can be avoided by decreasing the negative pressure and hence the ΔP. In 2005, Chintamani et al. [3] showed in a randomized controlled study that a half vacuum suction drain significantly reduced the hospital stay as compared to those on full suction vacuum drain after modified radical mastectomy for breast cancer without added morbidity. A good guide to the timing of decreasing the vacuum would be when the RBC settles on the tube with clear serum above. This indicates that the bleeding has stopped, and it is the serum that is draining [3].
4. An option that is increasingly being practiced across the world is to convert the vacuum drainage into regular tube drainage by connecting the tube to a drainage bag instead of the vacuum chamber. This prevents unnecessary tissue exudation at the site of the surgery and hastens drain removal and thereby the hospital stay.

Vascular Surgery

In vascular diseases, Poiseuille's law plays an important role. For example:

1. In cold-induced vasospastic disease (Raynauds disease), cold agglutinins are formed when the temperature drops. Increased intravascular particulate matter increases the viscosity of the blood flow (η) in the capillaries and smaller arterioles. Combined with cold-induced spasm, which decreases the radius of the blood vessels and hence decreases the flow (Q) to the fourth power, this precipitates ischemia to the extremities.
2. While closing an artery, especially a superficial femoral or a smaller artery, ideally, a transverse arteriotomy is performed, which is closed with continuous or interrupted fine polypropelene suture with no further compromise in flow. However, in case a vertical arteriotomy is made, then Poiseuille's law should be taken into account as with the subsequent healing of the diameter of the vessel is reduced affecting the flow, and hence, the arteriotomy should be covered with a small patch of vein and oversewn accordingly.
3. While correcting arterial narrowing at two or more sites, it is important first to address the proximal larger diameter lesion. As the flow changes with the radius to its fourth power, a small increase in radius in a large vessel results in a greater improvement in the blood flow in the smaller distal vessel. This result is a greater flow than that achieved by increasing the fractional diameter of the small distal vessel [2].
4. As the flow rate radius is raised to the fourth power, this principle should be borne in mind while repairing any hollow tubular organ like the intestine, bile duct, vas deference, fallopian tube, and ureters in addition to the blood vessels [2].

Intestinal Surgery

1. STEP procedure, serial transverse enteroplasty:

In patients with Crohn's disease with multiple strictures, as alternative to bowel resection and short bowel syndrome, the tendency these days is to proceed with a longitudinal enterotomy which is closed full thickness in a transverse direction like Mikulicz's pyloroplasty. This tranverse enteroplasty is repeated at all the stricture levels to increase the luminal diameter and to avoid losing vital small bowel mucosa in patients with Crohn's disease.

2. Right versus left colonic tumors:

In patients with right colonic cancers, obstruction is a late phenomenon. This is due to the nature of the tumor, exophytic rather than constricting, and also because of the content of the ileum, and the right colon is liquid compared to the left half of the colon. Low viscosity of the contents does not build up the resistance in the lumen, delaying diagnosis until a large mass is formed.

Fluid Resuscitation

Patients who are hypovolemic secondary to hemorrhage rapid fluid replacement is the key to resuscitation. Poiseuille's law is applicable here in more than one way.

1. Faster infusion can be achieved with a short bigger gauge of the cannula [4]. Additionally, blood infusion tubing having a wider diameter can deliver fluids double the rate that of standard infusion tubing.
2. Central venous catheter placement reduces the "L" of the vessels traversed assuring rapid filling of the atrium.
3. A shorter infusion set would keep L small.

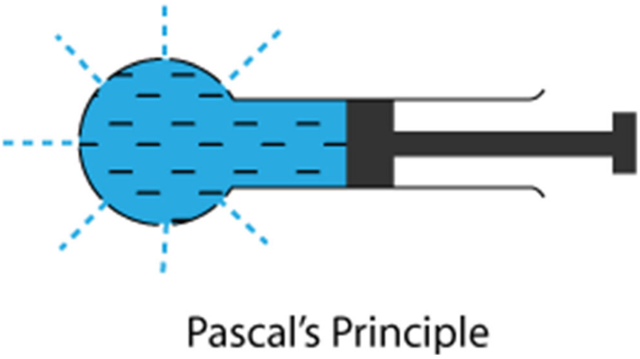
To sum it up, a wide-bore cannula with short wide infusion tubing (blood set) should be used at a venipuncture site closest to the right atrium on a wider vein (cephalic, basilic, jugular, or subclavian vein rather than on the long saphenous vein of the ankle, relatively narrow and far from the heart). Additionally, it is best to use crystalloid to keep the viscosity (η) low. Higher flow can be achieved by maximizing the pressure difference "ΔP" by applying a pressure cuff around the infusion bottle [2].

Tracheostomy

Tracheostomy to some extent decreases the dead space of the trachea bronchial tree traversed by inhaled air, and consequently reduces the L factor, which diminishes the resistance to airflow. This is particularly used in patients with less compliant lungs, as for example ARDS.

Pascal's Law

This law states that, in a closed container, any change in the pressure is equally transmitted in all directions. Force=Area × Pressure. The classical experiment to demonstrate Pascal's law is the rubber ball with a number of small perforations in it. Compressing the ball will cause fluid to spurt out from all directions with equal pressure. The following figures explain it schematically.



This law has got a number of important implications in abdominal surgery.

1. Abdominal compartment syndrome (ACS):

   The abdominal wall and the diaphragm represent the anterior and superior surface of a closed container. Any increase in intra-abdominal pressure would therefore be reflected on all sides equally.
   Abdominal compartment syndrome refers to organ dysfunction caused by intra-abdominal hypertension. The renal, cardiovascular, and respiratory are some among the other systems to be involved by virtue of compressing the inferior vena cava and pushing the diaphragm up. It usually goes unrecognized as it affects patients who are ill and admitted in the ICU. Since treatment can improve organ function, it is important that the diagnosis be considered when appropriate. It comes on following penetrating trauma, intraperitoneal hemorrhage, pancreatitis, postoperative state, large volume resuscitation, intra-abdominal sepsis, and various other conditions.
   For many years, it was a perplexing point to surgeons as to whether a patient was developing ACS and was only relieved by opening the abdomen to the exterior. Appreciation of Pascal's law has allowed us to extrapolate that intra-abdominal pressure would also be transmitted equally to the bladder. Therefore, measurement of the intravesical pressure through a Foley's catheter, a relatively simple adjunct to clinical monitoring of the patient, enables early detection of the onset of ACS. If the intravesical pressure increases beyond 15 mmHg, ACS is impending, and steps are taken immediately to reduce the pressure on the cava, like decompression.

2. Hernia Repair

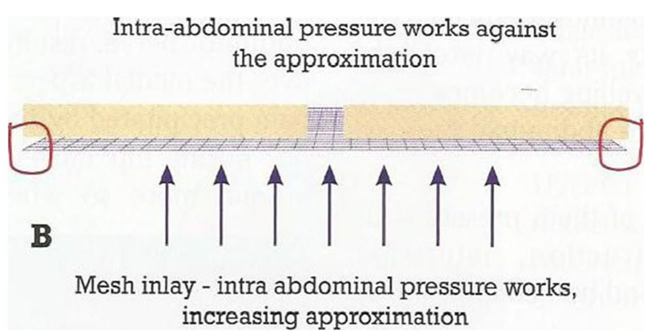
Application of Pascal's law will allow us to understand the biomechanics of mesh placement of abdominal wall hernias. When there is a leak in a hot air balloon or a bathtub, it is best repaired by sealing the defect from the inside. If sealed from the out, the pressure of the air or water will push the seal outwards and hence likely to fail. Now, let us consider the following types of hernia repair:

- Anatomical closure.
- Onlay mesh (placed in the subcutaneous plane).
- Inlay mesh (or intraperitoneal onlay mesh IPOM).

When the patient increases the intra-abdominal pressure while coughing or sneezing, this pressure is transmitted equally in all directions and therefore there will be divergent pressures on the edges of the repair, causing a high recurrence of incisional hernias after anatomical closure.

On the other hand, if an onlay mesh is placed superficial to the repair, then the forces of the intra-abdominal pressure act divergently on the wall and this is resisted by the presence of the mesh. However, though better than the former repair, there is still a propensity for failure as the forces are pushing the mesh outward. Here, success depends on how well the mesh is anchored to the fascial tissues.

When the mesh is placed between the peritoneum and the abdominal wall, the intra-abdominal pressure forces are actually acting in favor of the repair and are compressing the mesh against the anterior abdominal wall. Anchoring the mesh securely is just academic. Thus, the recurrence is very low in intraperitoneal onlay mesh placements. It is also important that the mesh overlaps the edge of the defect by at least 3–5 cm to allow Pascal's forces to act evenly on the mesh. A small wonder, that across the developed and developing countries, laparoscopic intraperitoneal onlay mesh is rapidly supplanting anatomical repair or repair plus onlay meshes.

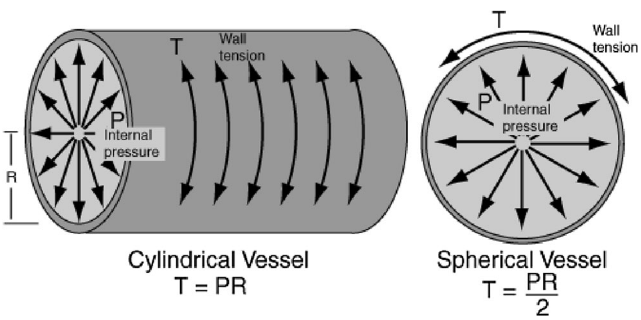


3. Heimlich maneuver [3]:

A technique for preventing suffocation when a foreign body blocks a person's airway works on the same principle. Compressing on the chest wall circumferentially with a sudden and abrupt pressure over the xiphisternum dislodges the foreign body. (Sudden pressure on a soft bottle will dislodge the lid).

Laplace's Law

This law states that tension in the wall of a closed container is product of the pressure and the radius.



That is, $2T=P\times R$, where T=tension on the wall, P=pressure within the chamber, and R=radius of the container. To understand Laplace's law in action, think of blowing a balloon. Greater effort is needed to blow an empty balloon than a partially inflated balloon, which has a larger diameter and hence needs lesser pressure to overcome the surface tension.

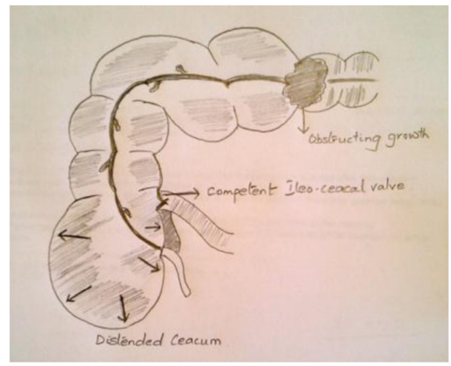
This has got very important consequences in surgery. For example:

1. Esophageal varices

We recognize that esophageal varices of grade III and IV has a much higher chance of rupture compared to grade I and II. Although this seems logical, there was a time when esophageal varices were not banded except if there were episodes of bleeding. In recent years, realization that the larger varices have a much higher tendency to spontaneously rupture has led to recommendation of endovariceal ligation of grade III and grade IV varices especially if patients are non-compliant or do not have access to prompt medical care. Grade III and grade IV varices have the same intravariceal pressure as the grade I and II, but a higher tension as the diameter is greater and therefore a propensity for a rupture.

2. Closed loop intestinal obstruction

In complete large bowel obstruction with a competent ileo-cecal valve, Laplace's law plays an important role. The entire colonic compartment from the ileo-cecal valve up to the constricting growth comprises one container with equal pressures all around (Pascal's law). Wherever the constriction, the cecum has the highest radius and therefore would develop the largest tension (please see figure), and therefore, it is the cecum that has a highest chance of cecal blowout or perforation.



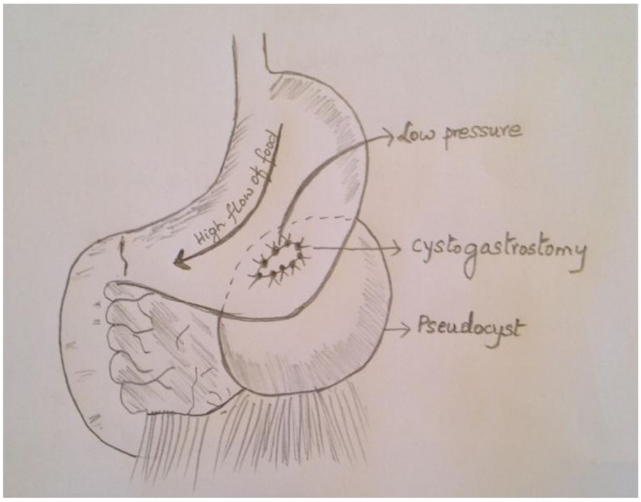
Bernoulli Equation or Theorem

Named after Daniel Bernoulli and in effect what the theorem says is:

An increase in the speed of the fluid occurs simultaneously with a decrease in pressure or its potential energy. The highest speed occurs where the pressure is lowest. This principle is used in aero- and hydrodynamics but is important to us as surgeons in the following situations:

1. Pseudocysto-gastrostomy

This procedure was first performed by Jedlicka, more than a hundred years ago. It remained a mystery for several decades as to why food from the stomach did not enter the retroperitoneal pseudocyst area, with the pseudocyst gradually undergoing decompression and then obliteration of the space. The actual reason is explainable by evoking Bernoulli's principle. The flow of food and liquid in the stomach is from the esophagus towards the antrum, and this causes a high forward flow. The high forward flow causes a pressure gradient between the pseudocyst cavity and the gastric cavity, and consequently, the flow only occurs from the pseudocyst to the stomach lumen, and not the other way around.



2. Sleeve gastrectomy

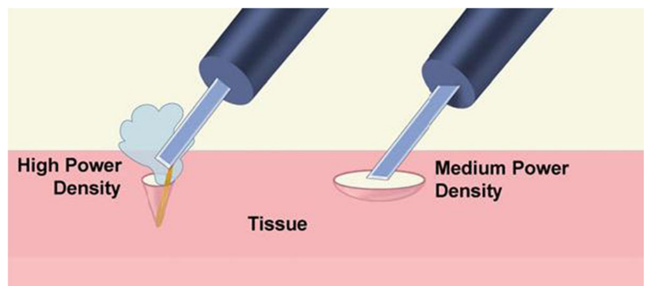
In a situation like a leaking sleeve gastrectomy, the leak usually occurs from the highest staples, very close to the esophagogastric junction. This is perpetuated by higher intragastric pressure, as the pyloric muscle is tough and patent, and acts as a barrier to pressures. Decreasing the intragastric pressure by a long transgastric stent is an almost definite remedy for this problem, as it decreases the flow into the leaked part of the stomach using Bernoulli's principle.

3. Enterocutaneous fistula

It is a common fact that fistulas do not close if there is a distal obstruction. Fluid tends to find the easiest pathway, and relieving the distal obstruction by Bernoulli's principle will increase the antegrade flow, causing a negative a pressure at the junction of the fistulous tract and the native lumen, and thus hasten its closure.

Ohm's Law

It is important that every surgeon understands the basics of Ohms law because there is almost no surgery without some form of electrocautery. Here, radiofrequency alternating current is used to raise the temperature of cells to cause desiccation and coagulation of proteins, with a net result of either cutting or coagulation (used for hemostasis of tissues). The term cautery is a misnomer, which literally means destruction of tissue by passive transfer of heat from a heated instrument, Greek *kauterion* (hot iron). The term *diathermy* which means "electrically induced heat" is more appropriate. The temperature rise of the tissue is affected by current (I), voltage (V), and impedance orresistance (R). It is measured in amperes, while voltage is measured as volts and resistance in ohms, while the ease with which the current passes is called conductance and measured as Siemens (S). This in simple term is the difficulty a given substance presents to the passage of electrons. When the current used is alternate current, the term impedance is used instead of resistance. Their relation is expressed as $I=V/R$ [5]. The most important knowledge for the surgeon that governs the effect of radiofrequency on the tissue is that of the current density. Current density, which is the current per unit area, is inversely proportional to the surface area of the dispersive electrode. Very high current density concentrated at the tip of an electrode can be used to heat and vaporize cells, and slightly lower current density may desiccate and coagulate while the same current spread over a large area may have no impact on the cells, the circumstance created by the design of a dispersive electrode. This is analogized to the effect of magnifying glass to focus the sunlight to start a fire [5].



The tissue conductance is one of the most important factors in adjusting the diathermy circuits. This explains different circuits used, for example for the underwater cutting in transurethral resection of prostate and the soft tissue diathermy current used in a hernia surgery. Appreciating the tissue conductance, the newer energy-based devices like the Forcetriad,[2] Ligasure,[3] etc. function using a linear circuit. There is constant feedback, and when the tissue conductance and impedance reach a particular level, it indicates a complete denaturation of protein and complete coagulation of all vessel walls. At this point, an auditory signal (beep) is given as a feedback, allowing the surgeon to press the trigger and cut the tissue. This concept in energy-based devices precludes the need for a continuous diathermic coagulation of tissues, which could result in excessive tissue damage and charring and increased risk of infection. It is the same principle of diathermy that underlies the need for keeping a high ratio between the surface pad and the point of entry of the electrical energy into the body. As the same electrical current enters and exits, it is only

[2] ForceTriad™Energy Platform- Covidien
[3] LigaSure™ Vessel Sealing Instruments, Covidien

the increased surface area at the point of exit that prevents the tissues from being burnt. Inadvertent displacement of diathermy pad will alter the ratio between the point of entry and the point of exit causing a diathermy burn.

Piezzoelectric Effect

Paul-Jacques Curie, French physicist along with his younger brother, Pierre Curie discovered piezoelectricity in 1880. Essentially, this isthe production of electricity by application of pressure, which is otherwise defined as a linear electromechanical interaction between the mechanical and electrical state. It is a reversible process, with the electricity production stopping on stoppage of the pressure. There is also a medically important inverse piezzoelectric effect in which there is an internal generation of a mechanical strain resulting from the application of an electrical field.

Lead or zirconate titanate crystals will change their dimension when an external electrical field is applied. This change reverses as soon as the electricity is switched off. Thus, pulses of electrical application result in rapid movement of the crystals, and this inverse piezzoelectric effect will produce ultrasonic waves when the vibration generates cycles of more than 10,000 Hz/s.

In practical terms, the ultrasonic shears[4] has become a very important part of the armamentarium of laparoscopic surgeons. In this instrument, the inverse piezzoelectric effect is used to create the vibration of a dynamic plate at the rate of 55, 000 cycles per second to generate ultrasonic waves. The other blade contains an insulated substance. This blade is the one that should be in contact with the surface of the tissue that is to be protected to avoid inadvertent damage in various operations. For example in the performance of Heller's myotomy for achalasia cardia, it is important to keep the vibrating blade on top and the indifferent blade against the mucosa when the circular muscle fibers are being taken down. Failure to do so might result in burning of the mucosa and delayed perforation. When applied in the vicinity of other instruments, the vibrating blade is kept away from the metal tips to avoid permanent damage of the hand probe during laparoscopic surgery.

Using the high-intensity focused ultrasound through the inverse piezzoelectric effect causes a localized implosion of tissues, called the cavitation effect. This is useful in the CUSAR (Cavitational Ultrasound Aspiration Resector) also known as the Cavitatron. In relatively homogenous tissue like the liver and lung, application of the CUSAR probe at the point of contact causes a violent implosive cavitational effect on the tissues and sucks out the parenchymal tissue leaving the collagen of the vessels undisturbed. Then, the surgeon can either tie and cut the vessels alone or use an ultrasonic or bipolar cutter on the vessels alone and then continue the resection of the liver or lung using the CUSAR.

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[4] HARMONIC® Ultrasonic Devices, Ethicon Endo-Surgery, Inc.