SOME ASPECTS OF THE MECHANICS OF THE ABDOMEN*

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The understanding of intra-abdominal mechanics has eluded research since the very early days of medical science. During the 19th century and up to the time of World War I, substantial investigation into abdominal dynamics was made. These researches fell into decline because of the difficulty of the project generally, and because it was regarded as impracticable to measure intra-abdominal pressures. However, during the World War II the subject obtruded itself again, presumably because of war wounds and the problems of aviation medicine.[1-3] It would be misleading to say that workers are lacking who have concerned themselves with abdominal mechanics. We have been unable, though, to discover much in the way of new publications of significance after 1950.

The large hiatus in our present-day knowledge is certainly noticeable when we attempt to explain the etiology of conditions such as paralytic ileus, acute dilatation of the stomach, uterine prolapse and displacements, enterocele, hernias, the mechanisms of parturition, defaecation and micturition, visceroptosis (if such a condition exists), oesophageal regurgitation and dyspepsia, board-like rigidity of the abdomen, etc.

Coffey,[4] in 1917, said, 'Except in chronic processes, such as the development of a tumour by cellular increase, a cyst or ascites which has behind it the blood pressure or pregnancy, there is but little change in the capacity of the abdomen of an otherwise normal person'. In 1922 Coffey[5] was still of the opinion that the abdominal walls were relatively inelastic. This he assumed to be an important factor in the 'splinting' of the abdominal contents and so increasing the intra-abdominal pressure; particularly when the deposition of intra-abdominal fat occurred, for instance, in obesity or in the West-Mitchell technique of the rest cure and forced feeding for neurasthenics and visceroptotics. Unfortunately no actual pressure-readings were taken and the conclusions were mostly assumptions.

Goffe,[6] in 1912, attempted to define intra-abdominal pressure, and I think his definition is as good as any I have come across. He defined it as 'the pressure within the abdomen due to external atmospheric pressure, to gravity, to muscular contraction of its walls, to intravisceral pressure'. Rushmer[3] would add to this 'the head of pressure provided by the mass of the movable organs within the peritoneal cavity' (which in fact is the same as gravity).

In those days, as today, the general impression prevailed that intra-abdominal pressure is negative and that under certain circumstances there is a tendency to produce vacuums. With this in mind, it was said that the organs in the abdominal cavity were held in place by this negative pressure, although the various ligaments might have something to do with it.

Sturmdorf[7] said that there was no muscle or ligament that could withstand the continuous force of the intra-abdominal pressure. These ligaments, according to him, support the organs not by virtue of their textural resistance, but by deflecting the displacing force of intra-abdominal pressure.

If it were true that the intra-abdominal organs maintained their relative positions by virtue of deflective forces pushing down on the one hand and supporting on the other, then one must postulate a central area in the abdominal cavity exerting pressure in all directions. Obviously the force supporting the under-surface of the liver must be diametrically opposed to that pressing down on the superior surface of the uterus. The answer is still unknown. Clearly there is no single factor which is solely responsible for the position of the viscera; but ligaments, intra-abdominal pressure and support from adjacent organs seem to be the most important.

In the strict physical sense the question may well be

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asked: Is there such a thing as intra-abdominal pressure? Can the abdominal cavity be considered as one physical unit? First of all, there is no abdominal cavity in the physical sense, except in the case of ascites, pneumoperitoneum or peritonitis, where there is a cavity filled with liquid, air, or both.

Unless there is fluid in the peritoneal cavity, the abdominal wall surrounds a multitude of organs tightly adjacent to each other and tightly adjacent to the wall; the interspaces between two organs, or between an organ and the abdominal wall, are merely potential. The serosa with its moisture, sees to it that no friction takes place on the one hand and that no spaces are created on the other.

For the present, I will consider the abdominal cavity as including the pelvic region as well. Thus the limits of the cavity are the very mobile diaphragm above, the pelvic floor below, the rather rigid spinal column behind, and in front and at the sides the fairly flexible and elastic muscular abdominal wall. Within these boundaries are the abdominal and pelvic organs, both solid and hollow, surrounded by their fat and peritoneum. The retroperitoneal plane, with its spongy connective tissue, fat and kidneys, does not participate to any degree in the present problem, the exceptions being retroperitoneal tumours encroaching on the capacity of the abdominal cavity.

One then assumes that the capacity of the abdomen is very variable, differing from subject to subject according to body build, muscular tone, obesity, posture, etc.

Being a striated muscle, the *diaphragm* is subject to cortical impulses and can be moved at will. However, unlike all other striated muscles, it retains its full coordinated function at a time when our voluntary control of striated muscles has partially or entirely ceased—during general anaesthesia and in coma. The cessation of diaphragmatic function causes death. There are many theories which attempt to explain the ambivalent position of the diaphragm, but none is very conclusive. The importance of the diaphragm in the consideration of abdominal physiology is very great. Normally it is continuously mobile and is the common factor in the changing pressures within the abdomen and thorax. Many believe that it is because of the pumping action of the diaphragm that a continuous circulation of the peritoneal fluid occurs.

Cane[8] says, 'There cannot be any question as to the existence of an over-all intra-abdominal pressure, and that the organ capable of increasing or diminishing the pressure is the diaphragm'.

Although one agrees that the diaphragm is probably the most active participant associated with variations in intra-abdominal pressure the powerful muscular wall of the abdomen must not be overlooked, for often the diaphragmatic position is secondary to the action of these muscles.

We know from every-day experience that intra-abdominal pressure certainly exists and is very variable; witness the individual trying to expel a hard stool, the woman in labour, and the prostatic in urinating.

It is an error to regard the abdomen as a rigid structure. The attitude should rather be that the boundary walls of the abdominal and pelvic cavities form one somewhat complex organ in themselves and that, to a major degree, the functions of the organs encased therein depend upon its state, and *vice versa*.

One may compare the abdomen to a sealed cylindrical rubber bag which is being suspended by its upper margins. This bag is also partially filled with liquid and the remaining air drawn off. The rubber wall is regarded as being the counterpart of the abdominal wall, and the liquid as simulating the abdominal contents.

One will find that no matter what the position of the bag is, the fluid will always find its own level. This will alter the shape of the bag accordingly.

In the vertical position the fluid will gravitate to the lower part of the cylinder and the rubber bag will assume a pear shape. The pressure above will then be much less than that at the bottom of the cylinder. This difference in pressure is due entirely to the difference of the levels of the water column measured. This increased pressure at the lower level has been shown to exist in both animals and the human being. Rushmer showed that this state existed in dogs. In our experiments we have shown that in the supine position intragastric and intrarectal pressures are identical, but that in the erect posture the intragastric pressure is less than the intrarectal pressure. This difference in pressure is equal to the pressure of a column of water between the two levels at which the readings were taken (Fig. 1).

In the horizontal position one finds that the bag flattens and tends to bulge at the sides. Obviously the degree of distension, bulging and flattening will depend upon the elasticity of the rubber wall; and in the human being upon the muscular tone of the antero-lateral abdominal wall. An anaesthetized patient, with a relaxed abdominal wall, in the supine position, will also tend to bulge in the flanks. This tension is the reason why air rushes into the peritoneal cavity when the peritoneum is opened. This has in the past created the misconception that the intraperitoneal pressure is a negative one.

One must then understand that with various alterations in the shape and position of the abdomen, variations in the intra-abdominal pressure will occur. The tendency to produce vacuums is halted by the fact that the external atmospheric pressure will always replace space by pushing inwards either the anterior abdominal wall, the diaphragm, or to a lesser extent the pelvic floor. Lower pressures are certainly obtained, but hardly ever a pressure less than that of the atmosphere.

As already indicated, the pressure immediately beneath the dome of the diaphragm may be less than that of the atmosphere. If the anterior abdominal wall is distended, then the diaphragm comes down in an attempt to retain the original volume. If the descent of the diaphragm is insufficient to do this, then one assumes that the gut dilates in order to occupy the remainder of the available space. The position is reversed when the abdominal wall is rigid and retracted. One then sees the diaphragm as a fixed dome at a higher level than normally.

In straining, however, the position is altered and one finds both the abdominal wall rigid and retracted, and the diaphragm pushed downwards. If a person strains hard enough something has to give way, and the result is the passage of either urine, flatus or faeces.

It has been stated that the diaphragm has an ambivalent nerve-supply and that it is subject to cortical impulses. The precise amount of control that the cortex has over the diaphragm is, however, questionable. One knows of no means whereby isolated diaphragmatic movements in the living human being can be studied. Movement of the diaphragm is always associated with movements of either abdominal wall or thoracic musculature. The more one attempts to move the diaphragm as an isolated muscle, the more one is impressed by the difficulty of so doing. It seems as though, to a great extent, the movement of the diaphragm is almost completely dependent upon thoracic and abdominal muscular activity. Can one cough without using the anterior abdominal wall? Can one breathe voluntarily without making use of either the abdominal or thoracic musculature?

PUBLISHED RESEARCH

The present-day knowledge of the actual intra-abdominal pressure is confusing. Pressure studies within the human intraperitoneal space have very rarely been reported. The subject is confused by misleading nomenclature, such as intra-abdominal pressure, intraperitoneal pressure, and intravisceral pressure.

In a review of the literature up to 1911 Emerson[9] cited 4 authors who stated that the intra-abdominal pressure was atmospheric, 6 that it was negative, 12 that it was positive and 5 that it was variable. Emerson himself made 24 experiments and he concluded that the intra-abdominal pressure was slightly positive. He also proved that under normal conditions there is no free gas to be found in the intraperitoneal cavity.

Keppich[10] (1921), using intraperitoneal needles in dogs and human subjects, concluded that the normal intraperitoneal pressure in man varies from 0·5 to 3·4 cm. of water.

Wildegans[11] (1924), measuring the intraperitoneal pressures in human beings, found that only in one case was the pressure negative, and this only during an inspiratory dyspnoea. The same author demonstrated that in order to introduce air into the peritoneal cavity, a positive pressure of 4 cm. of water was required in experimental rabbits and from 1·5 to 12 cm. of water in human beings. These subjects were all in the horizontal position and the abdominal wall was punctured near the umbilicus.

Wagoner[12] (1926) and Salkin[13] (1934) working with monkeys, rabbits, cats and dogs encountered intraperitoneal pressures fluctuating between -0·2 and -5·5 cm. of water.

Overholt[14] (1931) in dogs obtained pressures of -0·5 to -10 cm. of water.

Lam[15] (1939), by inserting rubber balloons into the peritoneal cavities of dogs, measured the pressures under varying conditions, and the majority of his readings were above that of atmospheric pressure. Lam also stated that in man in the erect posture there is a pressure of 25-40 cm. of water in the lower portion of the abdomen and in the pelvis. This pressure decreases as the upper part of the abdomen is reached, until under the dome of the diaphragm a negative pressure may be recorded. If the subject is standing on his head the pressure relationships are reversed.

The main point is that human abdominal pressures have not been taken directly as a regular technique. Direct measurement is essential and is the only thing that will explain certain mechanisms and suggest certain therapies dependent on change of pressure. A wide survey on this basis and with this simple approach, should lead to a full and valuable understanding of the mechanics of the abdomen.

AUTHOR'S TECHNIQUE

Up to the present time various and variable techniques have been used, and this has been the main cause of the chaos. Water manometers, rubber balloons, the closed-system manometer (Lewis) and a host of other ingenious and inaccurate apparatuses have been used. To appreciate the technical difficulties one must realize that the peritoneal cavity is a potential space and that there is a neglible amount of fluid present to act as a conductor of pressures. To overcome this difficulty, liquid or air must be introduced into the peritoneal space, and this immediately alters the original dynamics.

A suitable apparatus had to be found. To my knowledge, the apparatus best suited for this type of work is the electrical strain-guage attached to an amplifier and a recording unit. This is connected to the patient by means of a fairly rigid-walled polythene catheter of 1-2 mm. bore. For readings of intraperitoneal pressure this tubing is attached to a needle or a cannula, which is inserted into the peritoneal cavity.

To record intragastric pressures it was sufficient for the patient to swallow the tube until a positive pressure-reading was obtained, which indicated that the tip of the tube had passed through the 'negative pressure' area of the oesophagus into the stomach.

Bladder readings were made by connecting the polythene tube to a gum-elastic catheter after the bladder had been emptied.

In all the cases the polythene catheter filled with a fluid (usually normal saline) was sufficient for the satisfactory recording of pressure in almost any situation. A double-channel recorder was used so that simultaneous measurements from 2 different points or cavities could be made. The readings were very accurate and a record of the slightest variation was obtained.

Most of the subjects where intraperitoneal pressures were recorded were cases of ascites or those requiring intraperitoneal gold therapy for malignant disease. One case with uterine prolapse was utilized.

Bladder, rectal and gastric pressures were recorded in normal persons, including myself.

The very limited number of recordings have been made tend to show that the intra-abdominal pressures are from 5 to 25 cm. of water above that of the atmospheric pressure. The lower pressures are usually associated with expiration. On coughing, straining and attaining the erect position, a level of almost 100 cm. of water was reached.

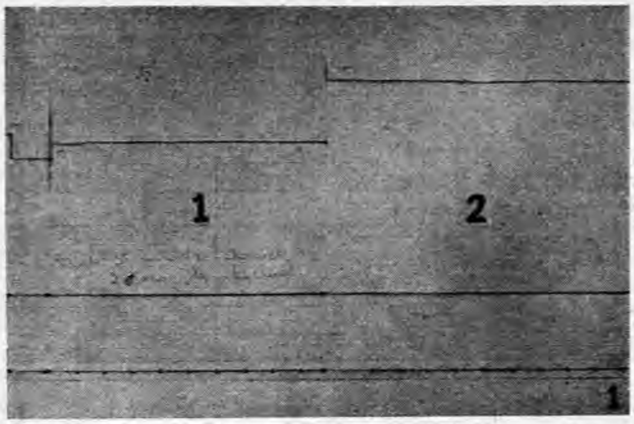

Fig. 1. Graph showing the difference between (1) intragastric pressure and (2) intrarectal pressure. The difference corresponds to the height of a column of water measured from the xiphisternum to the top of the symphysis pubis.

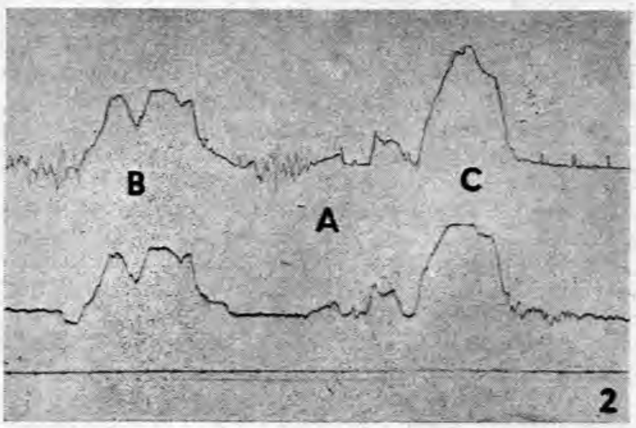

Fig. 2. Simultaneous recordings from the peritoneal cavity (above) and bladder (below) showing the similarity of pressure patterns at rest (A), on coughing (B) and on straining (C).

Simultaneous readings in the intraperitoneal cavity and bladder showed identical patterns and almost exactly similar pressures under various conditions and in different positions. Many more readings need to be made, but these results tend to show that for practical purposes one may use the empty bladder in order to measure intra-abdominal pressures.

APPLICATION

I had hoped to discuss many of the applications of the intra-abdominal dynamics. What happens in oesophageal regurgitation? Is it due to temporarily increased abdominal pressure? Is the mechanism of diaphragmatic hiatus hernia similar? What is the mechanism of acute dilatation of the stomach? How does the air get there and whence does it come?

What of uterine prolapse? Why does it almost always occur after the menopause? Is it due to the usual concurrent increase of weight with an associated increased intra-abdominal head of pressure?

The mechanisms of urination and defaecation have still not been explained satisfactorily. The study of the mechanism of defaecation is extremely complex, and so is the mechanism of expulsion of the foetus during labour.

These are but a few of the problems. Scores of others are also awaiting investigation and elucidation. Unfortunately, time will allow me to enlarge on only a few of these problems.

The first I shall refer to is the reaction of the abdomen in a rarefied atmosphere, a subject on which Professor Heyns has been working. Both Professor Heyns and I experimented with the cuirass that is placed over the thorax and abdomen in poliomyelitis cases. We found that when the cuirass was exhausted to a pressure of 500-300 mm. of mercury the girth of the abdomen increased by $1\frac{1}{2}$-4 inches. This confirms that the muscular abdominal wall is elastic and distensible, and opens up a new field.

The effect of a rarefied atmosphere is well known to the high-altitude pilot. He knows well the discomfort associated with an ascent after drinking gas-forming fluids. In rapid spins the pilot is in the centre of the rarefied atmosphere and this is associated with abdominal distension. This tends to interfere with the venous return from the lower extremities and abdomen to the thorax. This has led to the development of the 'anti-g' suit, which does not allow this abdominal distension and thus reduces the hazard of 'blackouts'. Decompression illness or the 'bends' is a well-recognized complication of rapid decompression.

Fowler's Position

It has always been assumed that free fluid in the peritoneal cavity gravitates downwards. With excessive amounts of fluid present the bulk of it will no doubt settle in the most dependent regions of the abdominal cavity. How then can the formation of a subphrenic abscess be explained, particularly in the patient being nursed in the Fowler's position? There are two main factors present. One is the capillary action of the thin film of fluid in the peritoneal 'spaces'. This is responsible for the upward displacement of a certain volume of intraperitoneal fluid.

The other factor is that of the low pressure to be found immediately beneath the dome of the diaphragm in relation to the pressure in the remainder of the abdominal cavity during expiriation. The pressure immediately beneath the dome of the diaphragm is closely related to that within the thorax, which is generally negative. The diaphragm, as it were, acts as a pump and its movement is to a major degree responsible for a continuous circulation of the peritoneal fluids within the abdominal cavity. There is thus access to the subphrenic spaces for intraperitoneal pus, other fluid and circulating malignant cells. This action ceases when a fluid level is produced by a pneumoperitoneum, as also, to a certain degree, does the capillary traction of the peritoneal fluid i.e., in the erect position.

Cunningham[16] has shown that normally there is an upward flow of the peritoneal fluids towards the subphrenic spaces, where it is absorbed and passes into the diaphragmatic lymphatics. Carmine particles injected into the peritoneal cavity have been shown to be present in the mediastinal lymphatics within as short a time as 3 minutes. Meig's syndrome may be a manifestation of this mechanism, where an attempt is being made to remove a pathological amount of fluid draining from the peritoneal cavity into the pleural cavity with the formation of a pleural effusion.

'Pot Belly' and Prolapse

I believe that the 'middle-age spread' one encounters in the male subject is the homologue of uterine prolapse in the female. How often does one encounter the so-called 'pot belly' in the female? Yet uterine prolapse is common.

In the male the inclination of the pelvic brim is of a greater degree than in the female. Moreover, the shape and measurements of the male pelvis lead to a smaller pelvic-floor exposed to pressure from above (Fig. 3).

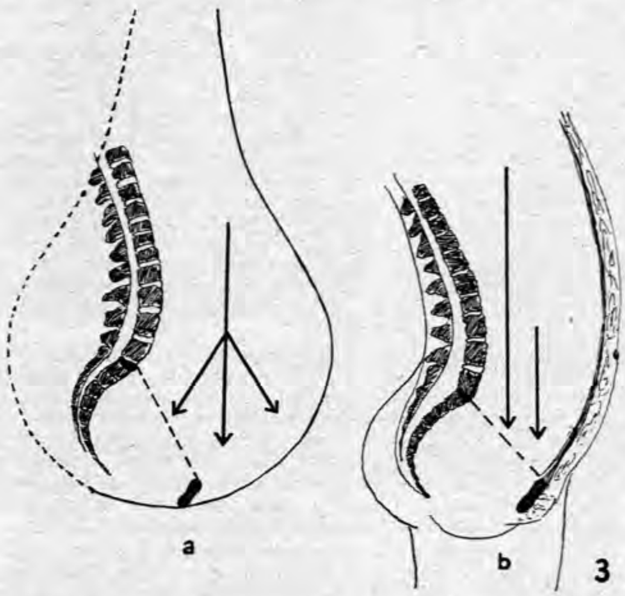

Fig. 3a. The highly tilted male pelvis allowing intra-abdominal pressure to fall mainly on the anterior abdominal wall. Note the pear-shaped contour.
(*b*) The more 'horizontal' female pelvis. This position causes a greater pressure to be exerted on the pelvic floor.

These male conditions are simulated by the female pelvis in the majority of the African Bantu; and uterine prolapse is a rarity in the Bantu female, but 'pot belly' a common feature, particularly in the younger age-groups.

In the European female the area of the pelvic floor is usually large and of gynaecoid shape, and pelvic tilt is more towards the horizontal. These factors suggest that the pressure exerted on the pelvic floor of the European female, in the majority of cases, is greater than either in the male pelvis or in that of the Bantu female.

Another factor probably playing an important role in the weakening of the pelvic floor musculature of the European female is the use of girdles and corsets. This practice is commonest immediately *post-partum*, and in my opinion it is an important etiological factor in the weakening and stretching of the pelvic floor. Bantu women, in whom pelvic-floor prolapse is rare, do not wear such apparel.

Middle-age spread is associated with an excessive increase in weight—the exception is the thin visceroptotic, atonic and asthenic person—and we have found that weight gain is also an associated factor at the time when patients develop uterine prolapse. The increased deposition of omental and visceral fat leads to an increased gravitational head of pressure in the presence of an abdominal wall or pelvic floor which has been gradually stretched and weakened as the result of ageing, lack of tone and, in the case of the pelvic floor, previous trauma.

In my opinion an increased intra-abdominal pressure is a factor in the etiology of uterine prolapse. This is borne out in women who develop complete uterine procidentia by straining excessively, e.g. in lifting of heavy objects.

It is noteworthy that hiatus hernia occurs in the same type of female as develops uterine prolapse, viz. postmenopausal multiparae with weight gain. The mechanism in this condition presumably being the increased weight on the diaphragm in the supine position.

CONCLUSION

There is still a vast field to be investigated. When we understand the physics and physiology of the abdominal cavity, only then shall we be able to solve many of our prevailing problems, and this will lead to prevention and the more rational approach to therapy. The study must not be confined to the cavity of the abdomen; the abdominal walls should also be considered. As with the diaphragm, the possibility of an ambivalent nerve-supply to the muscular abdominal wall should be investigated. One is not satisfied that the part played by the rectus muscle and the other flat muscles of the abdomen, in respect of postural and space-altering movements of the abdomen, is clearly understood.

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