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Abdominal compliance: A bench-to-bedside review

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Abdominal compliance: A bench-to-bedside review

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Abstract

Abdominal compliance is an important determinant and predictor of available workspace during laparoscopic surgery. Furthermore, critically ill patients with a reduced abdominal compliance are at an increased risk of developing intra-abdominal hypertension and abdominal compartment syndrome both of which are associated with high morbidity and mortality. Despite of this, abdominal compliance is a concept, which has been neglected in the past.

Abdominal compliance is defined as a measure of the ease of abdominal expansion, expressed as a change in intra-abdominal volume per change in intra-abdominal pressure:

abdominal compliance = delta intra-abdominal volume / delta intra-abdominal pressure.

AC is a dynamic variable, dependent on base-line IAV and IAP as well as reshaping and stretching capacity. Whereas abdominal compliance itself can only rarely be measured, it always needs to be considered an important component of intra-abdominal pressure. Patients with decreased abdominal compliance are prone to fulminant development of abdominal compartment syndrome when concomitant risk factors for intra-abdominal hypertension are present.

This review aims to clarify the pressure-volume relationship within the abdominal cavity. It highlights how different conditions and pathologies can affect abdominal compliance and which management strategies could be applied to avoid serious consequences of decreased abdominal compliance.

We have pooled all available human data to calculate abdominal compliance values in patients acutely and chronically exposed to intra-abdominal hypertension and demonstrated an exponential abdominal pressure-volume relationship. Most importantly, patients with high level of intra-abdominal pressure have a reduced abdominal compliance. In these patients, only small

reduction in intra-abdominal volume can significantly increase abdominal compliance and reduce intra-abdominal pressures.

A greater knowledge on abdominal compliance may help in selecting a better surgical approach as well as reducing complications related to intra-abdominal hypertension.

Background

Abdominal compliance (AC) together with the intra-abdominal volume (IAV) will determine the intra-abdominal pressure (IAP). Consequently, reduced abdominal compliance together with increased IAV can increase IAP and lead to intra-abdominal hypertension (IAH) and abdominal compartment syndrome (ACS). IAH and ACS are defined as a sustained IAP equal to or above 12 mmHg, and as a sustained IAP above 20 mmHg that is associated with new organ dysfunction/failure, respectively [1]. The incidence of IAH is high in the critically ill patient and is associated with adverse outcome [2]. ACS is a life-threatening condition with high mortality [2].

Moreover, AC will for a given intra-abdominal laparoscopic working pressure determine the resulting IAV and thus the available workspace to perform laparoscopic surgery [3].

Correct estimation of AC might help avoiding complications related to IAH and ACS, by identifying the patient with decreased AC, who is at increased risk of developing IAH and ACS. Measuring AC is complicated and often not feasible in the clinical setting. However, understanding theoretical concepts and practical aspects of its assessment and management may help clinicians providing optimal health care for critically ill patients as well as patients undergoing laparoscopic surgery.

This review aims to clarify the pressure-volume relationship within the abdominal cavity, the mechanisms influencing AC, and pathophysiological effects of reduced AC. We will also discuss treatment options when caring for patients with reduced AC.

Methods

The search of different databases (Pubmed, MEDLINE and EMBASE) with unlimited start date until September 2014 was performed using the search terms of “intra-abdominal pressure”, “abdominal pressure”, “abdominal volume” and “abdominal compliance”.

Articles were also selected from the reference lists. We limited the languages to English, German, and French.

For the creation of abdominal pressure-volume curves we included all available manuscripts with at least two available human intra-abdominal pressure-volume measurements.

Results

Definition of abdominal compliance, abdominal wall compliance and abdominal elastance

The updated consensus definitions the World Society of Abdominal Compartment Syndrome (www.wsacs.org) defines “abdominal compliance” as a measure of the ease of abdominal expansion, determined by the elasticity of the abdominal wall and diaphragm, and expressed as a change in IAV per change in IAP (L/mmHg) [1].

$$\mathrm{AC} = \text{delta IAV} / \text{delta IAP}$$

When describing the abdominal pressure-volume relationship the term AC is better suited than abdominal wall compliance, as both the abdominal wall and diaphragm are distensible.

Initial increases in IAV lead to a reshaping of the abdominal wall and the diaphragm with only minimally increasing IAP. Further increases in IAV however, will lead to stretching and pressurisation of the abdomen (see *Reshaping, stretching and pressurisation of the abdomen*).

The term abdominal wall compliance is reserved to describe the elastic tissue properties of the abdominal wall.

Abdominal elastance = delta IAP /delta IAV = 1 / abdominal compliance

AC is often preferred over the use of abdominal elastance due to the familiarities of clinicians with the concept of respiratory compliance. However, abdominal elastance might be easier to directly derive in clinical practice as the slope (gradient) on an abdominal pressure -volume curve (Figure 1).

Anatomy of the abdominal cavity enclosure

The anatomy of the abdominal cavity restricts the possibilities of volume expansion: The posterior wall is rigid due to the spine and the retroperitoneal organs, the lower abdominal wall is restricted by the pelvic bones. The upper abdominal wall constitutes of the diaphragm which can, if intra-abdominal pressure increases, expand into the chest with negative respiratory effects [4-7].

The elasticity of the anterior and lateral abdominal wall, and to less extent the diaphragm, determine the AC [1,8,9]. The anterolateral abdominal wall consists of skin, superficial fascia, fat, muscles with their aponeuroses, transverse fascia, and the parietal peritoneum.

The rectus abdominis muscle and its associated fascia is the principle muscle of the anterior, whereas the external oblique, internal oblique, and transverse abdominis muscles form the lateral abdominal wall.

It is thought that the anterior abdominal aponeurosis and to a lesser degree the abdominal muscles are the main structural components determining abdominal wall compliance [10]. The abdominal muscles have a composite-laminate structure, the extracellular matrix playing a key role in determining their non-linear stretch characteristics [10]. Transverse fascial fibres are responsible for the transverse stiffness of the abdominal wall, whereas the rectus abdominis muscle in the sagittal plane is less stiff [4,5].

Reshaping, stretching and pressurisation of the abdomen

When IAV is added to the abdominal cavity, three different phases can be distinguished: a) the reshaping phase with configuration changes and minimal change in IAP (small slope on the abdominal pressure-volume curve), b) stretching phase through elastic elongation of the abdominal wall and diaphragmatic tissue (medium slope), and c) pressure phase with the characteristic pressure-volume relationship found in a confined space (large slope). All three phases occur in parallel and overlap (see Figure 1).

These dynamic changes are partially dependent on resting (base-line) values of IAV and IAP. Resting IAV is different in each patient, there is no IAV defined to be normal or increased.-In 12 healthy adult subjects total IAV, assessed by computer tomography was estimated to be around 13 L [11].

Resting IAP (base-line IAP) will depend on the amount of abdominal cavity “prefilling” or the resting IAV in proportion to the reshaping capacity of the abdominal wall and diaphragm. Normal IAP ranges between 5-7 mmHg [8]. Assessment of IAP is described elsewhere [1].

In contrast to the intracranial compartment, adding volume to the abdominal cavity reshapes the abdominal wall and diaphragm [6,9,12]. This reshaping capacity can be described as the difference between "resting/base-line IAV" and the maximum IAV reached without increasing

IAP (the "maximal unstressed internal abdominal cavity surface area" before stretching of abdominal wall occurs). Reshaping capacity depends on age, sex, height, weight and comorbidities.

Usually, reshaping continues until the abdominal wall develops a circular shape [13], additional IAV results in stretching only [14] (Figure 1).

During the stretching phase IAV increases in parallel with IAP, with the magnitude of changes depending on compliance of the abdominal wall and diaphragm. A relatively large increase in IAV results in a minor increase in IAP in a person with highly compliant abdominal wall/diaphragm, whereas the same additional IAV results in remarkable increase in IAP in case of a stiff abdominal wall/diaphragm (Figure 1). Laplace's law has been used to describe the stress forces that occur within the abdominal wall [5]. The stress force in the transverse plane is thought to be nearly double that found in the sagittal plane [5]. At the end of the stretching phase the "maximal stressed internal abdominal cavity surface area" is reached. During pressurisation phase, IAP increases exponentially, whereas no further increase in dimensions is expected.

A decreased abdominal wall compliance does not necessarily lead to decreased AC and *vice versa*. In case of previous overdistension (e.g. after relevant weight loss, pregnancies) the abdominal wall itself may be less distensible due to tissue damage through previous over-distension. However, the "reshaping capacity" is increased, and larger IAV can be accommodated before IAP increases. Hence, the abdominal wall compliance is less important in determining the effective AC.

In summary, AC is dynamic, depending on base-line IAV and IAP, reshaping and stretching capacity. Both of the latter are dependent not only on abdominal wall structure and compliance but also on a shape, elasticity and function of the diaphragm. Mechanisms of thoraco-abdominal interactions are described in detail elsewhere [15,16].

Abdominal pressure-volume relationship

Similar to the intracranial or intrathoracic (respiratory) pressure-volume curves, an abdominal pressure-volume curve can be constructed by plotting resulting IAP values taken at different IAV (Figure 1).

Abdominal pressure-volume curves derived from all available data of patients chronically or acutely exposed to IAH are depicted in Figure 2 and 3, respectively.

Abdominal pressure-volume curve has often been described as following a linear relationship [17-20] but the studied IAPs were mostly below 15 mmHg and/or few IAP/IAV pairs were measured.

Abdominal pressure-volume curve more likely follows an exponential function as recently demonstrated experimentally [21]. Human data derived from laparoscopy and peritoneal dialysis support an exponential abdominal volume-pressure curve [22,23].

This exponential abdominal pressure-volume relationship (Figure 1) has fundamental clinical consequences, as the actual AC will depend on its position on the abdominal pressure-volume curve.

Thus, during normal physiological conditions an additional predefined IAV only minimally increases IAP. However, when the resting IAV and resting IAP are already elevated (presence of IAH), adding the same IAV will significantly further increase IAP. Categorizing AC values derived from different studies in relation to IAP demonstrates that AC decreases with increasing IAP in a non-linear AC – IAP manner (Table 3).

Consequently, in a patient suffering IAH/ACS removing only small IAV may dramatically improve the patient's condition. The exponential abdominal pressure-volume relationship also explains why a linear function has been described for laparoscopic workspace. With an IAP up to 12 mmHg the pressure-volume relationship is on the lower end of the exponential curve, showing pseudo-linear characteristics [23].

Indeed, with pressures up to 15 mmHg the pressure-volume relationship seems to be linear [17-19,23], but curves up exponentially when higher IAPs are examined [21-23] (Figure 1).

Individual pressure-volume curves cannot be predicted, but patients in whom reshaping capacity of abdominal wall (e.g. so-called central, abdominal or apple-shape obesity) or diaphragm is limited (e.g. COPD) are likely to have an unfavourable pressure-volume relationship. Such patients, when undergoing abdominal surgery or being admitted to the ICU, are at greater risk of IAH/ACS.

Assessment of abdominal compliance

AC measurements were performed in humans by assessing IAP at least at two different IAV levels before and after either gas insufflation during laparoscopy [4,22-25], intra-abdominal fluid addition (peritoneal dialysis) [17,23] or drainage (ascites, pancreatic fluid or serous fluid in trauma patients) [18,26-28], sometimes in an experimental setting [21,29].

The derived AC in adult humans ranges between 0.06 to 1.92 L/mmHg (Table 1)

[17,18,22,23,27,28,30-37]. AC decreases with increasing IAP levels and is reduced in patients that have not been chronically exposed to high IAP levels.

It was suggested that AC could be estimated by respiratory variation of IAP by calculating deltaIAP (difference between end-inspiratory and end-expiratory IAP) and that if all other parameters remain constant, then a rise in deltaIAP could reflect a decrease in AC [38].

Laparoscopic workspace

During laparoscopic surgery, filling the peritoneal cavity with gas lifts the abdominal wall [4,9,39]. The increase of IAV achieved is called the laparoscopic workspace [3]. Recent data suggests that in most patients with low anaesthetic risk laparoscopic cholecystectomy can be successfully performed with peritoneal insufflation pressures below 12 mmHg [40]. There is no comparable data in high-risk patients, however. Preoperative estimation of AC as a tool to identify high-risk patients would be desirable in planning alternative surgical approaches.

In case of a high resting IAP, and/or a non-compliant abdominal wall, the workspace is limited. Such insufficient workspace predicts a more difficult operation [41]. In morbidly obese patients, high resting IAP might be a more limiting factor than decreased elasticity of the abdominal wall. The minimum increase of IAV for a successful operation was not defined, but the greater the laparoscopic workspace the easier it is to perform laparoscopic manipulations [42]. Therefore, it is important to know that some conditions (previous pregnancy or laparoscopic surgery) may be rather protective, whereas others make the patient prone to insufficient laparoscopic workspace.

Factors and conditions influencing abdominal compliance (see Table 2)

1. *Age*

Decreased AC in elderly has been reported [20], probably explained by reduced elastic properties of abdominal wall. Theoretically, decreased abdominal compliance should be expected also in young athletic patients with strong abdominal muscles. This would correspond to personal experience of the authors, but of our knowledge, this has never been studied.

2. *History of abdominal surgery or pregnancy*

Previous abdominal surgery or pregnancy have been shown to increase abdominal compliance [43,44]. This can be explained by a gradual pre-stretching of the abdominal wall when exposed to higher IAP levels. Even a short period of pre-stretching (20 min) is sufficient to increase AC in pigs [9]. A gradual increase in IAV when maintaining target pneumoperitonal pressures was observed in patients undergoing gynecologic or bariatric laparoscopic surgery [44]. The AC changed less when pneumoperitoneum was applied for a very short time [44]. Patients with a history of laparotomy, laparoscopy or multiple pregnancies had greater AC at the start, but showed smaller increase in AC throughout the procedure. This finding suggests increased reshaping capacity but decreased abdominal wall compliance, i.e. a decreased stretching capacity in patients with previous temporary distension of the abdominal wall. Therefore, pre-stretching even with relatively low IAP applied during laparoscopy seems to cause permanent changes in abdominal wall structure, most likely lengthened fibres with diminished elastic retraction capability. As a result, “maximal internal abdominal cavity surface area” increases, and larger IAV are accommodated at equal pneumoperitoneal working pressures. After reaching maximum “reshaping capacity”, these previously overstretched fascia and muscular fibres may appear more rigid compared to undamaged fibres.

Two possible mechanisms reducing AC in patients with previous laparotomies are scarring of the abdominal wall, which may result in decreased distendability and adhesions between the abdominal wall and the intestines causing decreased mobility. Why reshaping capacity might be increased in this patient group [44] is not clear. Possibly a reduction in intra- abdominal mass (eg. following bowel resection) or in abdominal wall muscles or subcutaneous tissue mass following perioperative immobilization contribute.

3. *Obesity*

Morbidly obese patients have higher resting IAP between 9-14 mmHg [8,45,46], and central obesity seems to correlate with increased IAP [45]. Morbidly obese patients with predominant abdominal obesity (sometimes referred to as apple-shaped obesity) accordingly have only limited reserve to accommodate more IAV as they start with a higher “resting IAV”, and have already reshaped their abdomen into a more spheric shape, resulting in a decreased AC [8,47].

The effect of the increase in fat in the subcutaneous tissue of obese patients is thought to have a negative effect on the elastic properties of the abdominal wall. At the same time, thin muscular layer might rather increase the abdominal wall compliance. Therefore, the abdominal wall compliance is not directly related to the extent of obesity, but is rather individual. The mechanisms for decreased AC in obesity are 1) increased IAV resulting in decreased reshaping capacity (with adipose tissue being an important factor); and 2) gravitational weight of the abdominal wall resulting in increased resting IAP.

No correlation between the thickness of the *m. rectus abdominis* and abdominal compliance in morbidly obese patients has been found [48]. On the other hand, it is not excluded that well trained abdominal muscles in absence of obesity might lead to reduced abdominal wall compliance.

In case of relevant weight loss in obese, similarly to women after giving birth, the base-line IAV decreases, whereas the "maximal internal abdominal cavity surface area" stays relatively unchanged, and therefore reshaping capacity is increased.

4. *Chronic medical conditions*

In medical conditions with chronic exposure to higher IAP/IAV (e.g. ascites, peritoneal dialysis), the “reshaping capacity” (maximal internal abdominal cavity surface area) appears to increase when compared to acute conditions (Figures 2 and 3, Table 3).

In contrary, COPD is associated with decreased AC due to reduced reshaping capacity of diaphragm [49]. Moreover, fast increase in IAP leads to respiratory decompensation in patients with severe COPD.

5. *Acute changes in elastic properties of the abdominal wall*

Structural changes of the abdominal wall occur in patients with abdominal wall burns eschars or following surgery [4,50].Mesh repair for hernia induces abdominal wall stiffness and thereby decreases AC [51,52]. The application of adhesive drapes can change AC without influencing the abdominal wall structure [53].

6. *Critical illness*

IAH occurs in approximately in one third of critically ill patients. Although AC is not directly measured we know that when IAP increases then AC decreases. The mechanisms of IAH in critically ill patients are multiple such as a large positive cumulative fluid balance, bowel distension and mechanical ventilation. When a critically ill patient already has a high grade of IAH, small amounts of extra IAV will significantly increase IAP. *Vice versa*, reducing IAV even in small amounts can dramatically reduce IAP in such patients.

Increased intra-thoracic pressure in mechanically ventilated patients with reduced lung compliance (e.g. ARDS) or reduced chest wall compliance (e.g. thoracic burn eschars) limits the diaphragmatic reshaping capacity and thereby impair AC. So far the influence of raised intrathoracic pressures to further worsen IAH has been shown to be small [8,54].

Possible consequences of decreased abdominal compliance

The same increase in IAV may have minimal effect on IAP or can cause IAH and ACS in patients with normal vs. decreased AC respectively. IAH may lead to serious cardiovascular, respiratory, abdominal, neurological and other adverse effects [1,16]. Increased IAP leads to reduced venous return and thereby necessitates increased fluid loading, starting a vicious circle with further increase in IAP. The most severe form of IAH - ACS - is a situation where very high IAP is a main factor directly leading to hypoperfusion and organ failure. Such situation needs to be prevented, anticipated and/or avoided whenever possible, or if not, then immediately recognized and managed accordingly. In simple terms either IAV has to be removed (e.g. fluid removal via renal replacement therapy, ascites drainage, laparotomy with evacuation of a hematoma) or the “maximum internal abdominal cavity surface area” increased (e.g. by performing a decompressive laparostoma).

Management of abdominal surgical patients with decreased abdominal compliance

1. *Optimization of laparoscopic workspace*

In patients with predicted insufficient laparoscopic workspace, open surgery or weight loss before elective laparoscopy, should be considered. In bariatric surgery, which is becoming the most common laparoscopic procedure in most countries in Europe and North America that may be quite difficult to achieve, however. It has been suggested that in morbidly obese patients with severe cardiac or respiratory dysfunction decision against laparoscopic surgery could be the best option, as these patients are at high risk for intraoperative and postoperative complications related to pneumoperitoneum [46]. Such decisions need to be made on an individual basis.

Additionally, during laparoscopy the body position might help to optimize the laparoscopic workspace. Mulier et al. suggest that the straight Trendelenburg position with 20° results in optimal workspace for lower abdominal laparoscopic surgery in obese patients [55]. At the same time, flexing the legs in reverse Trendelenburg position (resulting in a “beach-chair position”) effectively improved workspace for upper abdominal laparoscopic surgery [55].

Higher working pressures could improve laparoscopic workspace, but cannot be recommended because of multiple side effects. Laparoscopic pressures >15 mmHg can be used only for limited time and under cautious monitoring of vital organ functions. If higher working pressures are needed, intermittent desufflation should be considered to limit the negative effects of IAP on organ function. Higher working pressures cannot be routinely recommended for obese patients with high resting IAP, because reduction of complications emerging from high IAP has not been confirmed in this patient group, cardiovascular and respiratory co-morbidities might even further complicate the situation.

2. *Closure of the abdomen*

In case of open surgery, AC becomes important with closure of the abdomen. Decreased AC can often be recognized only when it is difficult to close the abdomen. Patients with decreased AC are at increased risk of developing IAH and ACS, and of wound dehiscence postoperatively. Monitoring of IAP at the time of abdominal closure and in the first days after abdominal closure is advisable in patients with decreased AC. If IAP and/or airway plateau pressure remain unacceptably high abdominal closure may need to be postponed after medical optimisation of AC. The risk of open abdomen becomes justified when weighed against development of ACS or wound dehiscence, especially if early closure is aimed and achieved.

3. *Anaesthetic management*

Anaesthetic management in patients with decreased AC includes deep muscle relaxation as neuromuscular blocking agents (NMBA) can improve AC by reducing resting IAP [56]. However, no additional increase in abdominal wall compliance after muscle contractions are fully blocked according to train-of four (TOF) has been shown [56]. The risk of atelectasis and hypoventilation vs. high ventilatory pressures needs to be carefully weighed in each individual case.

Management of critically ill patients with decreased abdominal compliance

Monitoring of IAP is of utmost importance in critically ill patients [57] especially in patients with reduced AC. It is not clear, how moderately increased IAP influences outcome in an individual patient. One should be aware of unpredictable dynamics of IAP dependent on AC, however. To avoid excessive fluid overload and abdominal wall oedema after the initial period of resuscitation in the critically ill, a rather restrictive fluid management plan is important, as there is evidence that a cumulative positive fluid balance by day 3 is associated with increased morbidity and mortality [58]. Apart from judicious use of fluid, fluid removal can be achieved by a furosemide infusion and or via renal replacement therapy [58].

Percutaneous catheters are increasingly used to drain intra-abdominal fluids and have shown to successfully reduce IAP levels in patients with secondary ACS due to pancreatitis, liver cirrhosis with ascites, and after massive fluid resuscitation in patients with burns and sepsis [59,60].

Different modes and ventilatory pressures may have different impacts, but patient-ventilator asynchrony has probably the most negative effect on AC. Breathing against the ventilator always involves contraction of abdominal muscles and leads to increase in IAP [20]. Therefore, sufficient ventilatory pressures should be used to achieve optimal synchrony with pressure support mode [61]. In cases where adequate synchronization is difficult to achieve temporary use of NMBA with controlled mode should be considered. Identifying optimal PEEP level in patients with low AC and already elevated IAP still needs to be clarified.

Avoidance of ACS in patients with decreased AC is a real challenge as the possibilities to acutely increase AC are limited, and carry risks. Aggressive medical management can be trialled for a short period. Negative fluid balance may reduce IAV and possibly decrease AC, but is suitable and effective only in patients with fluid overload. NMB can improve AC by reducing resting IAP [56] and possibly slightly increase AC via progressive stretching over time. NMBA should be considered as a temporary measure until other treatment strategies have been implemented.

Verbeke et al. showed that progressive stretching with improvements in AC may take place in relatively short time (during elective laparoscopic procedure) making short term use of NMBA in the acute setting encouraging [44].

The last resort treatment of ACS is creating an open abdomen [1], as the only way to achieve a significant expansion of the intra-abdominal volume is to open the anterior abdominal wall.

Conclusions

AC is a measure of the ease of abdominal expansion expressed as change in intra-abdominal volume per change in intra-abdominal pressure (L/mmHg) and is to be distinguished from the abdominal wall compliance. AC can be assessed by measuring the difference in intra-abdominal pressure (IAP) caused after removal or addition of intra-abdominal volume (IAV), but is not assessable in patients without these interventions. Available data derived from multiple IAP / IAV measurements suggest that abdominal pressure-volume curve has a linear characteristic in lower, but changes to exponential in higher IAP range. Therefore, AC changes dynamics of IAP and *vice versa*, making systematic monitoring and interpretation of dynamics of IAP essential. Abdominal compliance is reduced in different conditions and pathologies.

Future research should to address bedside assessment of AC and refine respective management strategies for different patient groups is warranted.

Authorship

All authors equally participated in data acquisition, analysis and interpretation of data. All authors were actively involved in the drafting and revising of the manuscript. All authors have read and approved the final version of the manuscript.

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