Manu L. N. G. Malbrain

# Different techniques to measure intra-abdominal pressure (IAP): time for a critical re-appraisal

**Abstract** The diagnosis of intra-abdominal hypertension (IAH) or abdominal compartment syndrome (ACS) is heavily dependant on the reproducibility of the intra-abdominal pressure (IAP) measurement technique. Recent studies have shown that a clinical estimation of IAP by abdominal girth or by examiner's feel of the tenseness of the abdomen is far from accurate, with a sensitivity of around 40%. Consequently, the IAP needs to be measured with a more accurate, reproducible and reliable tool. The role of the intra-vesical pressure (IVP) as the gold standard for IAP has become a matter of debate. This review will focus on the previously described indirect IAP measurement techniques and will suggest new revised methods of IVP measurement less prone to error. Cost-effective manometry screening techniques will be discussed, as well as some options for the future with microchip transducers.

**Keywords** Intra-abdominal pressure · Intra-abdominal hypertension · Abdominal compartment syndrome · Intra-vesical pressure

## Introduction

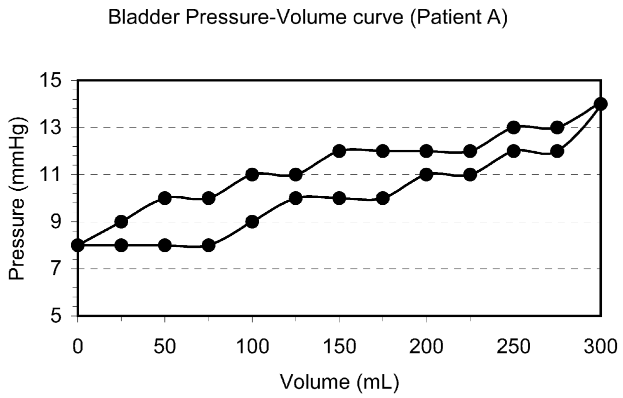
There is an exponential increase in studies on intra-abdominal hypertension (IAH) and abdominal compartment syndrome (ACS) in the literature. There is still controversy about the ideal method for measuring intra-abdominal pressure (IAP) [1, 2]. The intra-vesical route evolved as the gold standard. It, however, has considerable variability in the measurement technique, not only between individuals but also institutions. Common pitfalls are air bubbles in the system and wrong transducer positions. Variations in IAP from −6 to +30 mmHg have been reported previously [3]. A recent multicentre snapshot study showed that the coefficient of variation was around 25%, even up to 66% in some centres, raising questions on the reproducibility of the measurement itself. This makes it, difficult to compare literature data [4].

The volumes reported in the literature for bladder priming before the IAP measurement are not uniform (ranging from 50 to 250 ml). Injecting over 50 ml in a noncompliant bladder will raise intrinsic vesical pressure (IVP) and thus overestimate IAP [5, 6] (Fig. 1). By constructing bladder pressure volume curves we found that IVP was not raised when the volume instilled was limited to 50–100 ml [7] (Fig. 2). This is in accordance with others who found that baseline IAP alters the amount of volume in the bladder needed to increase IAP: the lower the baseline IAP, the higher the extra bladder volume needed for the same IAP increase [6].

The purpose of this report is: (1) to review the most commonly used indirect techniques for IAP measurement; (2) to provide the reader with a full description and important (dis)advantages of each technique; (3) to describe some new or revised techniques; and (4) to highlight the cost-effectiveness of each method.

M.R. Pinsky et al. (eds.), *Applied Physiology in Intensive Care Medicine*,
DOI: 10.1007/978-3-642-01769-8_30, 

Panel A




Panel B

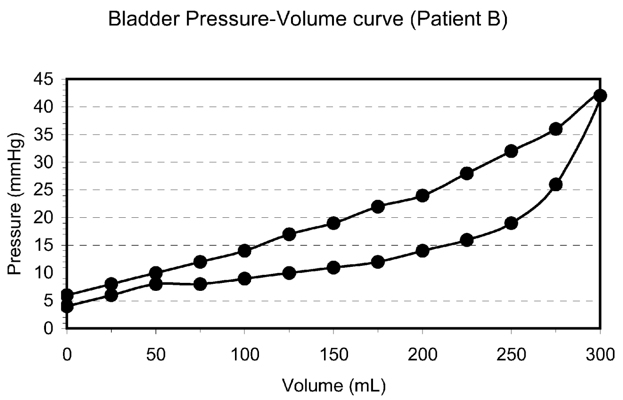



**Fig. 1 A** Bladder PV curve in a patient with a compliant bladder. Note that pressures are higher during insufflation than during deflation. Note that regardless of the amount of saline instilled in the bladder the pressures are comparable: 10 mmHg at 50 ml, 11 mmHg at 100 ml and 12 mmHg at 200 ml. **B** Bladder PV curve in a septic patient with a poor bladder compliance. Note that pressures are higher during insufflation than deflation. Note the significant difference in IAP value with regard to the amount of saline instilled in the bladder: 10 mmHg at 50 ml, 14 mmHg at 100 ml and 24 mmHg at 200 ml

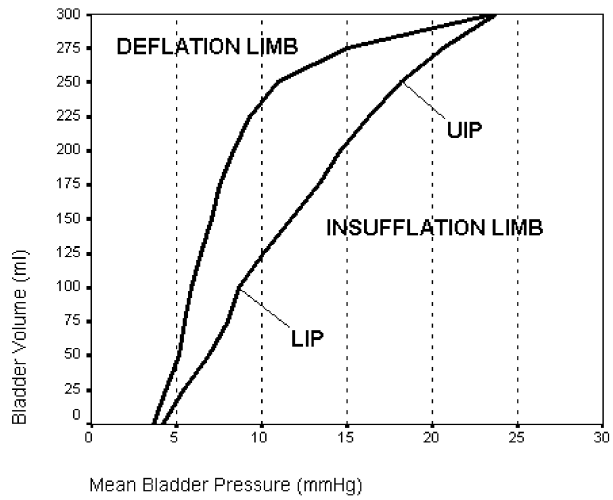



**Fig. 2** Plot of the "insufflation" and "deflation" PV curve as a curve fit of the means of 13 measurements in six mechanically ventilated patients. The bladder PV curves were obtained by instilling sterile saline into the bladder with 25-ml increments. A lower inflection point can be seen at a bladder volume of 50–100 ml and an upper inflection point (UIP) at a bladder volume of 250 ml. The difference in bladder pressure was 2.7±3.3 mmHg between 0 and 50 ml volume, 1.7±1.2 mmHg between 50 and 100 ml, 7.7±5.7 mmHg between 50 and 200 ml and 16.8±13.4 mmHg between 50 and 300 ml. See text for explanation

## IAP assessment

In analogy with the paradigm "if you don't take a temperature you can't find a fever" (in Samuel Shem, *The house of god*, Dell Publishing, ISBN: 0-440-13368-8), one can state that "if you don't measure IAP you cannot make a diagnosis of IAH or ACS". Abdominal perimeter cannot be used as an alternative method for IAP. In a recent study of 132 paired measurements in 12 ICU patients, we found a poor correlation between IAP and abdominal perimeter ($R^2$=0.12, $P$=0.04) [8]. Clinically significant IAH may be present in the absence of abdominal distension [9]. Chronic abdominal distension with sufficient time for adaptation, as seen with pregnancy, obesity, cirrhosis, or ovarian tumours, is an example of increased abdominal perimeter that is not necessarily accompanied by an increase in IAP. Other studies have shown that clinical IAP estimation by putting one or two hands on the abdomen is also far from accurate, with a sensitivity of only around 40%. So, one needs to measure it [10–12]. The question then arises: how? Since the abdomen and its contents can be considered as relatively non-compressive and primarily fluid in character, subject to Pascal's law, the IAP can be measured in nearly every part of the abdomen. Different direct and indirect measurement methods have been reported.

Table 1 lists the different techniques and their major advantages and disadvantages, with an overall score calculated by dividing twice the number of advantages by the total number of (dis)advantages reported. Table 2 lists the cost estimate in Euros for the different techniques, with the cost of the initial set-up as well as the cost per measurement. Cost estimations were based on the number of measurements per day as well as the duration of the measurement period.

**Table 1** Overview of the advantages (-) and disadvantages (+) of the different techniques for indirect IAP measurement. The overall score was calculated as the fraction of twice the number of advantages and the total number of (dis)advantages

| General information | Bladder techniques | | | | Manometry | | |
|---|---|---|---|---|---|---|---|
| Author | Kron | Iberti | Cheatham | Malbrain | Harrahil | Lee | Malbrain |
| Reference | [13] | [16, 17] | [18] | Current | [26] | [27] | [28] |
| Publication year | 1984 | 1987, 1989 | 1998 | 2003 | 1998 | 2002 | 2002 |
| **Properties** | Fluid | Fluid | Fluid | Fluid | Fluid | Fluid | Fluid |
| General — Volume | 50 ml | 250 ml | 50 ml | 50 ml | ? | ? | 50 ml |
| Manipulation | +++ | ++ | + | + | - | - | - |
| Difficult | + | - | + | - | - | - | - |
| Time consuming initial set-up | +++ | ++ | + | + | - | - | - |
| Time consuming next measurement | +++ | ++ | - | - | - | - | - |
| Cost of device initial set-up | + | + | + | + | - | - | - |
| Cost per measurement | ++ | ++ | + | + | - | - | - |
| Interference urine output | + | + | + | + | - | - | - |
| Glass syringe | - | - | - | - | - | - | - |
| Technique | | | | | | | |
| No repeated measurements | + | + | - | - | - | - | - |
| No continuous trend | + | + | + | + | + | + | + |
| Not automated | + | + | + | + | + | + | + |
| Recalibration | + | + | + | + | - | - | - |
| Volume not standardised | + | + | + | + | + | + | - |
| Not accurate or reproducible | + | + | + | + | + | + | + |
| Not well validated | - | - | - | - | + | + | + |
| Air-bubbles | + | + | + | + | + | + | + |
| Multiple menisci | - | - | - | - | + | + | + |
| Bio-filter blocking | - | - | - | - | - | - | + |
| MMC interference | - | - | - | - | - | - | - |
| Hydrostatic fluid column | | | | | | | |
| Zero-reference problem | + | + | + | + | - | - | - |
| Over-under damping | + | + | + | + | + | + | + |
| Body position dependent | ++ | ++ | ++ | ++ | ++ | ++ | ++ |
| Risks | | | | | | | |
| Needle stick injury | + | + | + | - | - | - | - |
| Urinary infection | + | + | + | + | - | - | - |
| Sepsis | - | - | - | - | - | - | - |
| Contra-indications | | | | | | | |
| Bladder trauma | + | + | + | + | + | + | + |
| Neurogenic bladder | + | + | + | + | + | + | + |
| Hematuria | + | + | + | + | + | + | + |
| Gastric trauma | - | - | - | - | - | - | - |
| Other abdominal trauma | - | - | - | - | - | - | - |
| **Overall conclusion** | | | | | | | |
| Disadvantages | 30 | 26 | 21 | 19 | 13 | 13 | 13 |
| Advantages | 8 | 9 | 10 | 12 | 18 | 18 | 18 |
| Overall score | 34.8% | 0.9% | 48.8% | 55.8% | 73.5% | 73.5% | 73.5% |
| Clinical indications | None | None | Screening | Intermittent monitoring | None | ? | Quick screening |

## Bladder

### The original open system single measurement technique [13]

*Description*

Traditionally the bladder has been used as the method of choice for measuring IAP. The technique was originally described by Kron and co-workers [13] and disrupts for each IAP measurement what is normally a closed sterile system. Thus, IAP measurement involves disconnecting the patient's Foley catheter and instilling 50–100 ml of saline using a sterile field. After reconnection, the urinary drainage bag is clamped distal to the culture aspiration port. For each individual IAP measurement a 16-gauche needle is then used to Y-connect a manometer or pressure

**Table 1** (continued)

| **General Information** | **IVC** | **Uterus** | **Rectum** | **Stomach** | | | |
|---|---|---|---|---|---|---|---|
| Author<br>Reference<br>Publication | Lacey<br>[29]<br>1987 | Dowdle<br>[31]<br>1997 | Shafik<br>[30]<br>1997 | Collee<br>[20]<br>1993 | Sugrue<br>[21, 22]<br>1994, 2000 | Malbrain<br>Current<br>2003 | Malbrain<br>Current<br>2003 |
| **Properties** | Fluid | Microchip | Fluid-filled balloon | Fluid | Air-filled balloon | Air-filled balloon | Air-filled balloon |
| General-Volume | | | ? | 50 ml | 2 ml | 1–2 ml | 0.1 ml |
| Manipulation | ++ | +++ | +++ | ++ | + | + | - |
| Difficult | + | ++ | ++ | + | + | + | - |
| Time taken for initial set-up | ++ | ++ | ++ | ++ | ++ | + | + |
| Time taken for next measurement | - | ++ | ++ | ++ | + | - | - |
| Cost of device initial set-up | ++ | ++++ | ++ | + | +++ | ++ | ++ |
| Cost per measurement | - | - | - | ++ | - | - | - |
| Interference urine output | - | - | - | - | - | - | - |
| Glass syringe | - | - | - | - | + | + | - |
| Technique | | | | | | | |
| No Repeated measurements | - | + | + | + | - | - | - |
| No continuous trend | - | + | + | + | - | - | - |
| Not automated | + | + | + | + | + | + | - |
| Recalibration | + | + | + | + | + | + | - |
| Volume not standardised | - | + | + | + | + | + | - |
| Not accurate or reproducible | + | + | + | + | - | - | - |
| Not well validated | +++ | +++ | ++ | + | + | + | + |
| Air-bubbles | + | + | + | + | - | - | - |
| Multiple menisci | - | - | - | - | - | - | - |
| Bio-filter blocking | - | - | - | - | - | - | - |
| MMC interference | - | - | - | + | + | + | - |
| Hydrostatic fluid column | | | | | | | |
| Zero-reference problem | + | + | + | + | - | - | - |
| Over-under damping | + | + | + | + | - | - | - |
| Body position dependent | + | ++ | ++ | ++ | - | - | - |
| Risks | | | | | | | |
| Needle stick injury | + | - | - | - | - | - | - |
| Urinary infection | - | - | - | - | - | - | - |
| Sepsis | +++ | - | - | - | - | - | - |
| Contra-indications | | | | | | | |
| Bladder trauma | - | - | - | - | - | - | - |
| Neurogenic bladder | - | - | - | - | - | - | - |
| Hematuria | - | - | - | - | - | - | - |
| Gastric trauma | - | - | - | + | + | + | + |
| Other abdominal trauma | - | + | + | - | - | - | - |
| **Overall conclusion** | | | | | | | |
| Disadvantages | 21 | 28 | 25 | 24 | 15 | 12 | 5 |
| Advantages | 16 | 13 | 13 | 11 | 18 | 19 | 26 |
| Overall score | 60.4% | 48% | 50.1% | 47.8% | 70.6% | 76% | 91.2% |
| Clinical implications | ? | None | ? | Screening | Research | Research | APP trend, Research |

transducer. The symphysis pubis is used as reference line. (See ESM addendum 1.)

*Advantages and disadvantage (Table 1)*

This technique implicates a lot of time-consuming manipulations that disrupt a closed sterile system at every measurement. It has all the problems that come along with the hydrostatic convective fluid column. Even though zero-reference at the symphysis pubis poses no problem, the problems come when the same pressure transducer is used for IAP and CVP, with zero-reference at the midaxillary line. Putting the patient upright with concomitant rise in the transducer may lead to underestimation of IAP, while putting the patient in the Trendelenburg position can lead to overestimation. The fact that recalibration needs to be done before every measurement augments the risk for errors. We have all seen the "magic" drop or rise in CVP at changes of nurse shifts, the same

**Table 2** Cost estimation (in Euros) of the different IAP measurement techniques: cost of initial set-up and next measurement, as well as cost projection based on number of IAP measurements per day and duration of measurement period. The cost evaluation was based on the following estimates: transducer: €24.75; 50 ml of saline: €0.3; syringe: €0.36; needle: €0.023; Foley catheter: € 0.53; nasogastric tube: €0.53; oesophageal catheter (Ackrad): €55; tonometer (Datex): €175; IAP catheter (Spiegelberg): €100; Foleymanometer (Holtech): €17.5; rectal/uterinel probe: €34.8; microchip transducer (Rehau): €1,250; conical connector: €2.2; male-male connector: €0.4; stopcock: €0.31; sterile drapings: €1.36; nursing costs: €25 per hour

| Technique | Author | Reference | Set-up cost | Cost per measurement | 2 times per day | | | | 6 times per day | | | | 12 times per day | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1week | 2weeks | 3weeks | 4weeks | 1week | 2weeks | 3weeks | 4weeks | 1week | 2weeks | 3weeks | 4weeks |
| Bladder | Kron. | [13] | 30.6 | 3.7 | 5.9 | 4.8 | 4.4 | 4.3 | 4.4 | 4.1 | 3.9 | 3.9 | 4.1 | 3.9 | 3.8 | 3.8 |
| | Iberti | [17] | 30.2 | 2.7 | 4.8 | 3.8 | 3.4 | 3.2 | 3.4 | 3.0 | 2.9 | 2.9 | 3.0 | 2.9 | 2.8 | 2.8 |
| | Cheatham | [18] | 31.3 | 1.3 | 3.7 | 2.6 | 2.3 | 2.1 | 2.1 | 1.7 | 1.6 | 1.6 | 1.7 | 1.5 | 1.5 | 1.4 |
| | Malbrain | Current | 34.7 | 1.0 | 3.6 | 2.3 | 1.9 | 1.7 | 1.8 | 1.4 | 1.3 | 1.2 | 1.4 | 1.2 | 1.1 | 1.1 |
| Stomach | Collee | [20] | 29.9 | 2.3 | 4.5 | 3.4 | 3.1 | 2.9 | 3.1 | 2.7 | 2.6 | 2.5 | 2.7 | 2.5 | 2.5 | 2.4 |
| | Malbrain | Current | 101.7 | 0.1 | 7.4 | 3.7 | 2.5 | 1.9 | 2.5 | 1.3 | 0.9 | 0.7 | 1.3 | 0.7 | 0.5 | 0.4 |
| | Sugrue | [21] | 202.7 | 0.3 | 14.7 | 7.5 | 5.1 | 3.9 | 5.1 | 2.7 | 1.9 | 1.5 | 2.7 | 1.5 | 1.1 | 0.9 |
| | Malbrain | Current | 83.7 | 0.3 | 6.2 | 3.2 | 2.2 | 1.8 | 2.2 | 1.3 | 0.9 | 0.8 | 1.3 | 0.8 | 0.6 | 0.5 |
| Rectal | Shafik | [30] | 70.1 | 0.2 | 5.2 | 2.7 | 1.8 | 1.4 | 1.8 | 1.0 | 0.7 | 0.6 | 1.0 | 0.6 | 0.4 | 0.4 |
| Manometry | Lee | [27] | 1.2 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| | Malbrain | [28] | 18.2 | 0.3 | 1.6 | 1.0 | 0.8 | 0.7 | 0.8 | 0.6 | 0.5 | 0.4 | 0.6 | 0.4 | 0.4 | 0.4 |
| Vena cava | Lacey | [29] | 66.3 | 0.2 | 4.9 | 2.5 | 1.8 | 1.4 | 1.8 | 1.0 | 0.7 | 0.6 | 1.0 | 0.6 | 0.4 | 0.4 |
| Microchip | Dowdle | [31] | 1278.1 | 0.1 | 91.4 | 45.7 | 30.5 | 22.9 | 30.5 | 15.3 | 10.2 | 7.7 | 15.3 | 7.7 | 5.2 | 3.9 |

can happen with IAP. Furthermore, a fluid-filled system can produce artefacts that further distort the IAP pressure waveform. Failure to recognise these recording system artefacts can lead to interpretation errors [14]. It can oscillate spontaneously, and these oscillations can distort the IAP pressure curve. The performance of a resonant system is defined by the resonant frequency (this is the inherent oscillatory frequency) and the damping factor (this is a measure of the tendency of the system to attenuate the pressure signal). Therefore, any fluid-filled system is prone to changes in body-position and over- or underdamping due to the presence of air-bubbles, a tubing that is too compliant or too long, etc. A rapid flush test should, therefore, always be performed before an IAP reading in order to obtain an idea of the dynamic response properties and to minimise these distortions and artefacts [16]. Confirmation of correct measurement can be done by inspection of respiratory variations and by gently applying oscillations to the abdomen that should be immediately transmitted and seen on the monitor with a quick return to baseline (Fig. 3). In case of a damped signal the flush test should be repeated.

Other disadvantages are: it is an intermittent technique that interferes with urine output without the possibility of obtaining a continuous trend, it places the patient at increased risk of urinary tract infection or sepsis, and subjects healthcare providers to the risk of needle stick injuries and exposure to blood and body fluids [13]. In conclusion, the Kron technique has at the present time no clinical implications.

The closed system single measurement technique [16, 17]

*Description*

Iberti and co-workers reported the use of a closed system drain and transurethral bladder pressure monitoring method [16, 17]. Using a sterile technique they infused an average of 250 ml of normal saline through the urinary catheter to purge catheter tubing and bladder. The bladder catheter is clamped and a 20-gauche needle is inserted through the culture aspiration port for each IAP measurement. The transducer is zeroed at the symphysis and mean IAP is read after a 2-min equilibration period. (See ESM addendum 2)

*Advantages and disadvantages (Table 1)*

It has the same disadvantages related to the hydrostatic fluid column as the Kron technique, and since it is not needle-free it also subjects health care workers to needle-stick injuries [10, 11].

The advantage compared with the Kron technique is that it is simpler, less time-consuming, and there are fewer manipulations. In conclusion, the Iberti technique

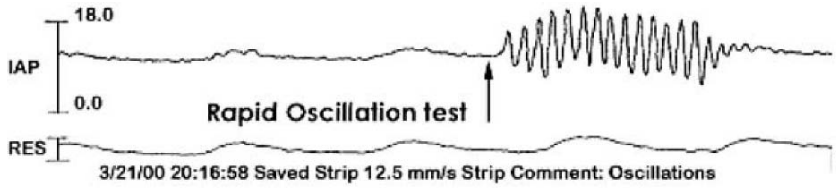



**Fig. 3** Confirmation of correct IAP measurement can be done by inspection of respiratory variations and by gently applying oscillations to the abdomen that should be immediately transmitted and seen on the monitor with a quick return to the baseline

has at the present time limited clinical implications (e.g. screening for IAH).

## The closed system repeated measurement technique [18]

*Description*

Cheatham and Safcsak reported a revision of Kron's original technique [18]. A standard intravenous infusion set is connected to 1,000 ml of normal saline, two stopcocks, a 60-ml Luer-lock syringe and a disposable pressure transducer. An 18-gauche plastic intravenous infusion catheter is inserted into the culture aspiration port of the Foley catheter and the needle is removed. The infusion catheter is attached to the pressure tubing and the system flushed with saline. (See ESM addendum 3.)

*Advantages and disadvantages (Table 1)*

It has the same inconveniencies related to any fluid-filled system as described with the Kron and Iberti techniques. It can pose problems after a couple of days because the culture aspiration port membrane can become leaky or the catheter kinky, leading to false IAP measurement. The fact that the infusion catheter needs to be replaced after a couple of days could increase the infection risk and needle-stick injuries.

This technique has minimal side effects and complications, e.g. without an increased risk for urinary tract infection [19]. It is safer and less invasive, takes less than 1 min, is more efficient with repeated measurements possible and thus is more cost-effective [18]. This technique is ideal for screening and monitoring for a short period of time (a couple of days) because of leakage.

## The revised closed system repeated measurement technique

*Description*

The technique of Cheatham and Safcsak was modified (Fig. 4), as follows. A ramp with three stopcocks is inserted in the drainage tubing connected to a Foley catheter (Fig. 4A). A standard infusion set is connected to a bag of 1,000 ml of normal saline and attached to the first stopcock. A 60-ml syringe is connected to the second stopcock and the third stopcock is connected to a pressure transducer via rigid pressure tubing. The system is flushed with normal saline and the pressure transducer is zeroed at the symphysis pubis (or the midaxillary line when the patient is in complete supine position). Figure 4B shows a picture of the device in a patient with a close-up of the manifold set with conical connectors. (See ESM addendum 4.)

*Advantages and disadvantages (Table 1)*

It has the same inconveniencies related to a fluid-filled system as described with the Kron, Iberti or Cheatham technique. This technique has the same advantages as the Cheatham technique, with a required nursing time less than 2 min per measurement, a minimized risk of urinary tract infection and sepsis since it is a closed sterile system, the possibility of repeated measurements and reduced cost. Since it is a needle-free system it does not interfere with the culture aspiration port and the risk of injuries is absent. This technique can be used for screening or for monitoring for a longer period of time (2–3 weeks).

## The revised closed system repeated measurement technique

In an anuric patient, continuous IAP recordings are possible via the bladder using a closed system connected to the Foley catheter after the culture aspiration port or directly to the Foley catheter using a conical connection piece connected to a standard pressure transducer via pressure tubing (Fig. 5). After initial "calibration" of the system with 50 ml of saline and zeroing at the sypmhysis pubis, the transducer is taped at the symphysis or thigh and a continuous IAP reading can be obtained. Daily calibration can be done in oliguric patients after voiding of rest diuresis.

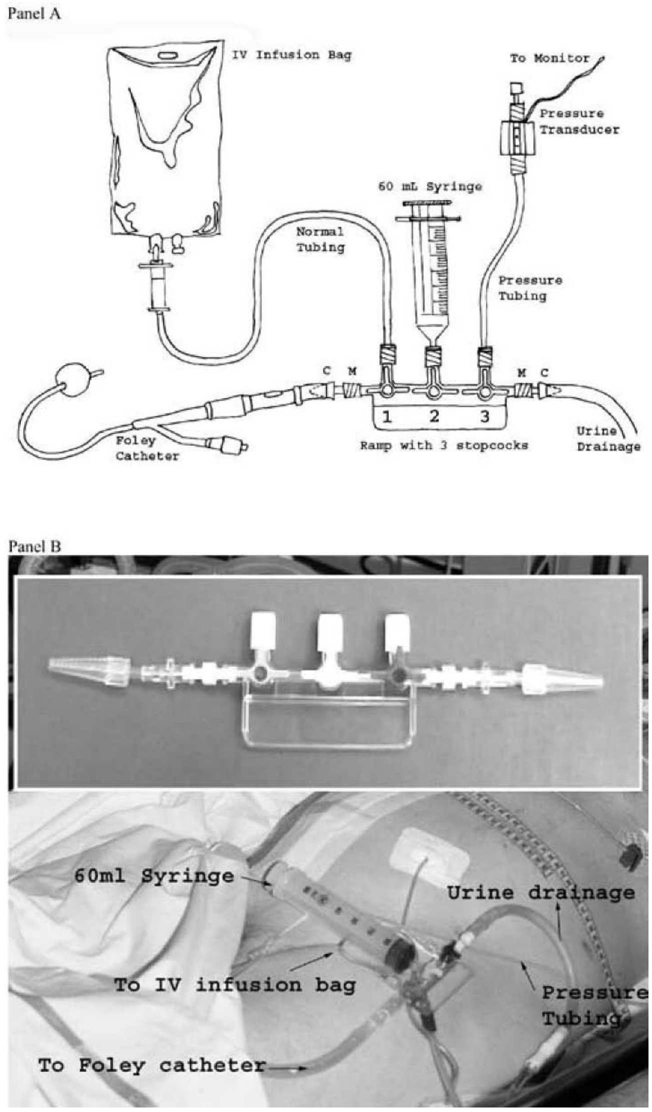



**Fig. 4 A** A closed needle-free revised method for measurement of intra-abdominal pressure. A standard intravenous infusion set is connected to a bag of 1,000 ml of normal saline and attached to the first stopcock. A 60-ml syringe is connected to the second stopcock and the third stopcock is connected to a pressure transducer via rigid pressure tubing. The system is flushed with normal saline and the pressure transducer is zeroed at the symphysis pubis. To measure IAP, the urinary drainage tubing is clamped distal to the ramp-device, 50 ml of normal saline is aspirated from the IV bag into the syringe and then instilled in the bladder. After opening the stopcocks to the pressure transducer mean IAP can be read from the bedside monitor. See ESM addendum 4 for explanation. **B** Mounted patient view of the device and close up of manifold and conical connection pieces

Conclusion

In conclusion, if one wants to use IVP as estimate for IAP the Cheatham or revised technique is preferred over the Kron or Iberti technique. The revised methods for IAP measurement via the bladder maintain the patient's Foley catheter as a closed system, limiting the risk of infection. Since these are needle-free systems they also avoid the risks of needle-stick injury and overcome the problems of leakage and catheter knick in the method described by Cheatham. They are more cost-effective, and facilitate repeated measurements of IAP.

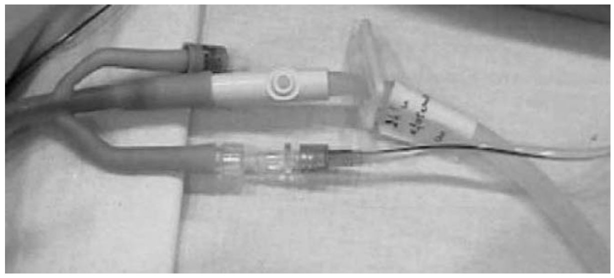


**Fig. 5** Close up view of a closed needle-free system for continuous intra-abdominal pressure measurement in an anuric patients, using a conic connection piece (conical connector with female or male lock fitting; B Braun, Melsungen, Germany — Ref. 4896629 or 4438450) connected to a standard pressure transducer via pressure tubing

## Stomach

The classic intermittent technique [20]

*Background and description*

The IAP can also be measured by means of a nasogastric or gastrostomy tube and this method can be used when the patient has no Foley catheter in place, or when accurate bladder pressures are not possible due to the absence of free movement of the bladder wall. In case of bladder trauma, peritoneal adhesions, pelvic haematomas or fractures, abdominal packing, or a neurogenic bladder, IVP may overestimate IAP, and the procedure used for the bladder can then be applied via the stomach [20]. (See ESM addendum 5.)

*Advantages and disadvantages (Table 1)*

The same inconveniences as with every fluid-filled system apply. Another disadvantage is that gastric pressures might interfere with the migrating motor complex or with nasogastric feeding. Furthermore all air needs to be aspirated from the stomach before measuring IAP, something that is difficult to verify.

The advantages are that it is cheap, does not interfere with urine output, and the risks of infection and needle-stick injuries are absent. This cost-effective technique is ideal for screening.

## The semi-continuous technique [21, 22]

*Background and description*

Sugrue and co-workers assessed the accuracy of measuring simultaneous IVP and IAP via the balloon of a gastric tonometer during laparoscopic cholecystectomy [21]. They found a good correlation between both methods. This technique allows a trend to be obtained. We recently validated these results and found good correlation between the classic gastric method, the tonometer method and IVP [22]. Simultaneous IAPtono and PrCO2 measurement was also possible. (See ESM addendum 6.)

*Advantages and disadvantages (Table 1)*

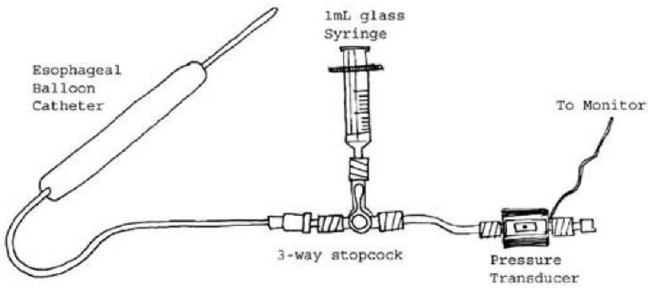
Measurement via the tonometer balloon limits the risks and has major advantages over the standard intravesical method: no infection risk and no interference with estimation of urine output. Simultaneous measurement of IAP and PrCO2 is possible; however, only in an intermittent way. Since it is air-filled it has none of the disadvantages associated with fluid-filled systems: no problem with zero-reference, over- or underdamping or body position. A possible disadvantage is the effect on interpretation of IAP values by the migrating motor complex. Recording the "diastolic" value of IAP at end-expiration can solve this problem. Other problems are that a 5-ml glass syringe is needed and that no data are available on effects of enteral feedings on these IAP measurements. This technique could be used for study purposes and clinicians interested in simultaneous CO2 gap and IAP monitoring.

## The revised semi-continuous technique

*Description*

An oesophageal balloon catheter is inserted into the stomach. When the balloon is in the stomach, the whole respiratory IAP pressure wave will be positive and increasing upon inspiration in case of a functional diaphragm. If the balloon is too high in the thorax the pressure will flip from positive to negative on inspiration measuring oesophageal or pleural pressure instead. A standard three-way stopcock is connected to a pressure transducer (Fig. 6A). All air is evacuated from the balloon with a glass syringe and 1–2 ml of air reintroduced to the balloon. The balloon is connected via a "dry" system to the transducer, the transducer itself is NOT classically connected to a pressurized bag and *not* flushed with normal saline in order to avoid air/fluid interactions. The transducer is zeroed to atmosphere and IAP is read end-expiratory. Figure 6B shows a close-up of the oesophageal balloon catheter. (See ESM addendum 7.)

Panel A




Panel B

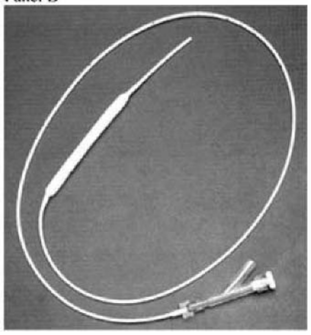


**Fig. 6 A** An oesophageal balloon catheter is inserted into the stomach (Oesophageal balloon catheter set, adult size with PTFE coated stylet; Ackrad Laboratories, Cranford, N.J., USA — Ref. 47-9005, see at http://www.ackrad.com/products/c-balloon_catheter.cfm or compliance catheter female or male, International Medical Products, Zuthpen, Netherlands, distributed by Allegiance — Ref. 84310). A standard three-way stopcock is connected to the now "nasogastric" tube; one end is connected to a pressure transducer via arterial tubing. All air is evacuated from the balloon with a glass syringe and 1 ml of air reintroduced to the balloon. A glass syringe is recommended to minimize the risk of pulling a negative pressure inside the catheter prior to reintroducing the 1 ml air. The balloon is connected via a "dry" system to the transducer, the transducer itself is *not* classically connected to a pressurized bag and *not* flushed with normal saline in order to avoid air/fluid interactions. The transducer is zeroed to atmosphere and IAP is read end-expiratory. See text for explanation. **B** Close-up view of the oesophageal balloon catheter

*Advantages and disadvantages (Table 1)*

A disadvantage is that the air in the balloon gets resorbed after a couple of hours (Fig. 7), so that "recalibration" of the balloon is necessary with a 2–5 ml glass syringe for continuous measurement, this might cause inaccurate measurement if the nurse waits too long for recalibration or if the re-instilled volume is not exactly the same as the previous one. It is less time-consuming and has all the advantages of an air-filled system (cfr tonometer). By

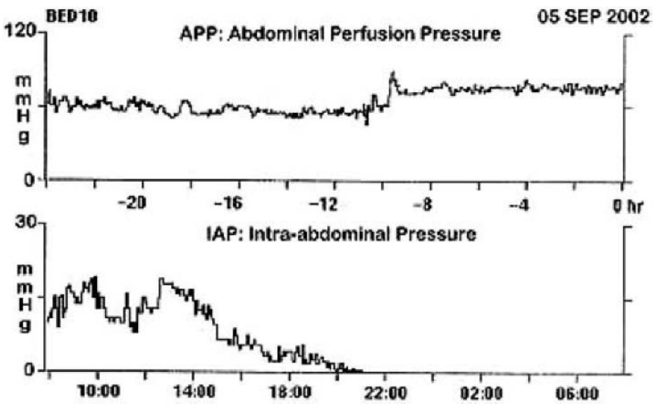



**Fig. 7** A trend of 24-h IAP and APP recordings obtained with an oesophageal balloon placed in the stomach (Ackrad). Note the resorption of air after a couple of hours, with loss of IAP signal, confirming the need for recalibration

using this technique the cost of IAP is further reduced depending on the catheter used. Moreover, a semi-continuous measurement of IAP as a trend over time is possible. The oesophageal balloon catheter price ranges from €15 (International Medical Systems, The Netherlands) to €55 (Ackrad, USA). This technique is ideal for monitoring for a longer period of time; however, when using multiple tubes the risk of sinusitis or infection needs to be evaluated in the future.

## The continuous fully-automated technique

### *Description: IAP measurement with the air-pouch system*

The IAP-catheter is introduced like a nasogastric tube; it is equipped with an air pouch at the tip. The catheter has one lumen that connects the air-pouch with the IAP-monitor and one lumen that takes the guide wire for introduction. The pressure transducer, the electronic hardware, and the device for filling the air-pouch are integrated in the IAP-monitor. Once every hour the IAP-monitor opens the pressure transducer to atmospheric pressure for automatic zero adjustment. The air-pouch is then filled with a volume of 0.1 ml required for accurate pressure transmission. Initial validation in ICU patients and laparoscopic surgery showed good correlation with the standard IVP method [23]. Recently Schachtrupp and co-authors used the same technique to directly measure IAP in a porcine model and found a very good correlation between the air pouch system and direct insufflator pressure ($R^2$=0.99) with a mean bias of 0.5±2.5 mmHg and small limits of agreement (–4.5 to 5.4 mmHg) [24]. (See ESM addendum 8.)

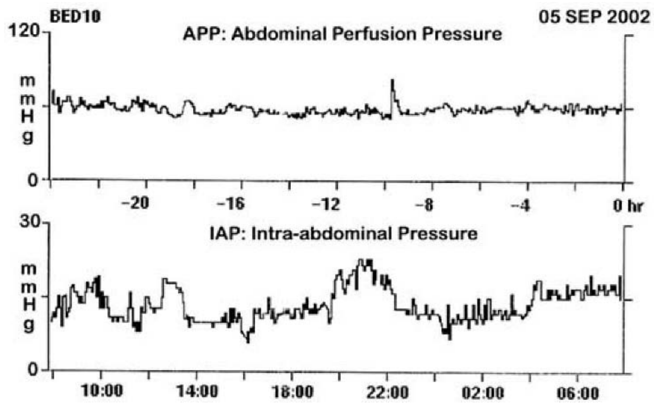



**Fig. 8** A continuous trend of 24-h IAP and APP recordings obtained with the Spiegelberg balloon-tipped IAP catheter placed in the stomach. Note the absence of resorption of air due to automated recalibration every hour. Note also the effect of CAPD fluid inflow on IAP. If IAP was measured only twice a day the fluctuations and peak pressures would have been missed

### *Advantages and disadvantages (Table 1)*

This technique has no major disadvantage except that validation in humans is still in its infant stage. The advantages are those related to other gastric and air-filled methods. In summary, it is simple, fast, accurate, reproducible, and fully automated, so that a real continuous 24-h trend can be obtained (Fig. 8). This technique is not suited for screening, but is best for continuous fully automated monitoring for a long period of time. Since it is less prone to errors and most cost-effective if in place for a longer period of time, this technique has a lot of potential in becoming the future standard for multicentre research purposes.

## Conclusion

The revised methods via the stomach have the advantage of being free from interference caused by wrong transducer positions, since the creation of a conductive fluid column is not needed as air is used as the transmitting medium. The last described fully automated technique also gives a continuous tracing of IAP together with abdominal perfusion pressure (APP) in analogy with intracranial pressure and cerebral perfusion pressure, allowing both parameters to be monitored as a trend over time. The APP is calculated by subtracting IAP from the mean arterial blood pressure. Recent data showed the importance of APP as a superior marker for IAH to titrate better the resuscitation of patients with IAH and ACS, hence avoiding end-organ failure and associated morbidity and mortality [2, 25].

## Manometry

The classic technique [1, 2, 26]

*Description*

A quick idea of the IAP can also be obtained in a patient without a pressure transducer connected by using his own urine as the transducing medium, first described by nurse Harrahill [1, 2, 26]. One clamps the Foley catheter just above the urine collection bag. The tubing is then held at a position of 30–40 cm above the symphysis pubis and the clamp is released. The IAP is indicated by the height (in cm) of the urine column from the pubic bone. The meniscus should show respiratory variations. This rapid estimation of IAP can only be done in case of sufficient urine output. In an oliguric patient 50 ml saline can be injected as priming. (See ESM addendum 9.)

*Advantages and disadvantages (Table 1)*

It has all the inconveniencies that come along with a fluid-filled system as described before. However, since it is needle-free it poses no risks for injuries. It allows repeated measurements, is very inexpensive and fast with minimal manipulation. Since the volume re-instilled into the bladder is not constant raising questions on accuracy and reproducibility, it has limited clinical implications.

The U-tube technique [27]

*Description*

In a recent animal study, Lee and co-workers compared direct insufflated abdominal pressure with indirect bladder, gastric and inferior vena cava pressures [27]. IVP was measured by both the standard and U-tube technique. With the U-tube technique, the catheter tubing was raised approximately 60 cm above the animal to form a U-tube manometer, and IVP was measured as the height of the meniscus of urine from the pubic symphysis. The authors found a good correlation between the U-tube pressure and other direct and indirect techniques. (See ESM addendum 10.)

*Advantages and disadvantages (Table 1)*

It has the same advantages and inconveniences as the classic “Harrahill” technique, as with the previous technique the clinical validation is poor. The major advantage of this technique is that the volume re-instilled into the bladder is more stable (but still not well defined), so it can be used as a quick screening method.

The Foleymanometer technique [28]

*Description*

We recently tested a prototype (Holtech Medical, Copenhagen, Denmark) for IAP measurement using the patients’ own urine as pressure transmitting medium [28]. A 50 ml container fitted with a bio-filter for venting is inserted between the Foley catheter and the drainage bag (Fig. 9A). The container fills with urine during drainage; when the container is elevated, the 50 ml of urine flows back into the patient’s bladder, and IAP can be read from the position of the meniscus in the clear manometer tube between the container and the Foley catheter (Fig. 9B). We found a good correlation between the IAP obtained via the Foleymanometer and the “gold standard” in 119 paired measurements ($R^2$=0.71, $P$<0.0001). The analysis according to Bland and Altman showed that both measurements were almost identical with a mean bias of 0.17±0.8(SD) mmHg (95% CI 0.03–0.3). (See ESM addendum 11.)

*Advantages and disadvantages (Table 1)*

It has the same inconveniencies and advantages as the other manometry techniques. It allows repeated measurements, is very cost-effective and fast, with minimal manipulation. The great advantage with the Foleymanometer is that the volume re-instilled into the bladder is standardised at 50 ml; therefore, it is preferred over the other manometry techniques. A major drawback is the possibility of occasional blocking of the bio-filter, leading to overestimation of IAP in some cases and the presence of air-bubbles in the manometer tube, producing multiple menisci leading to misinterpretation of IAP. Further refinement and multicentric validation needs to be done before being used in a clinical setting.

Conclusion

The manometry techniques give a rapid and cost-effective idea of the magnitude of IAP and may be as accurate as other direct and indirect techniques. They can easily be done two-hourly together with and without interfering with urine output measurements. Moreover, the risk of infection and needle stick injury is absent. Since they need to be validated in a multicentre setting they are not ready for general clinical usage at the present moment.

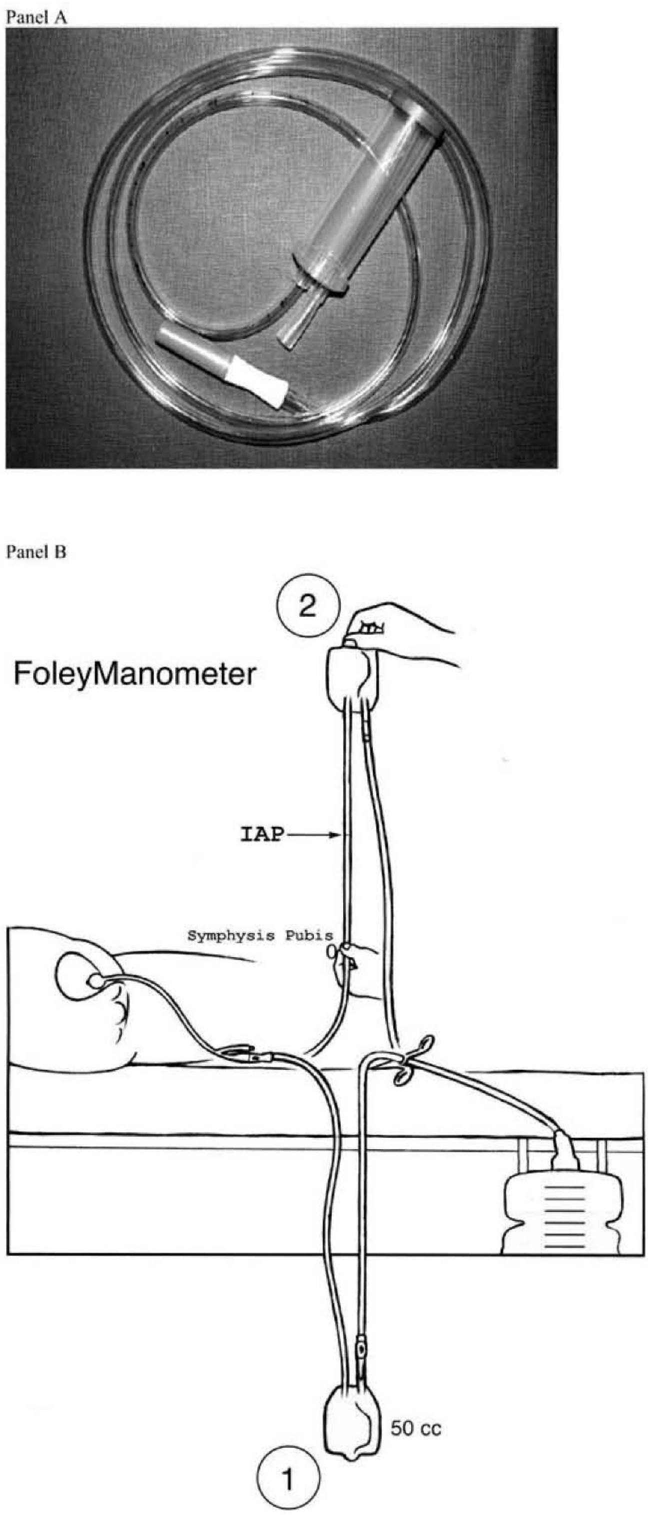



**Fig. 9** **A** The Holtech Foleymanometer: second prototype consists of a 50 ml container fitted with a bio-filter for venting inserted between the Foley catheter and the drainage bag. **B** The use of the Holtech Foleymanometer: schematic drawing. The container fills with urine during drainage (position 1); when the container is elevated (position 2), the 50 ml of urine flows back into the patient's bladder, and IAP can be read from the position of the meniscus in the clear manometer tube between the container and the Foley catheter

## Rectal pressure

Description

Rectal pressures are used routinely as estimate for IAP during urodynamic studies to calculate the transmural detrusor muscle pressure as IVP minus IAP [29, 30]. Rectal pressures can be obtained by means of an open rectal catheter with a continuous slow irrigation (1 ml/min), but special fluid-filled balloon catheters are used more routinely, although are more expensive. (See ESM addendum 12.)

Advantages and disadvantages (Table 1)

The major problem with the open catheter is that residual faecal mass can block the catheter-tip opening leading to overestimation of IAP. Other disadvantages of this technique are that it is more difficult, implicates more manipulation, is intermittent, and cannot be used in patients with lower gastro-intestinal bleeding or profound diarrhoea. There is also a great reluctance among nurses to use it. Since it is fluid-filled, it has all the problems associated with a hydrostatic fluid column, but since it is needle-free it decreases patient and healthcare worker infections or injuries. The fluid-filled balloon catheters are more expensive and, even though could theoretically stay in place for a longer period of time, interfere with gastro-intestinal transit and can cause erosions and even necrosis of the anal sphincter and rectal ampulla. Finally these techniques have not been validated in the ICU setting. This technique has no clinical implications in the ICU setting.

## Uterine pressure

Description

Basically this technique is mostly done with the same catheters as for the rectal route. Uterine pressures are used routinely by gynaecologists during pregnancy and labour. Most classically a standard so-called "intra-uterine pressure catheter" (IUPC) is used for this purpose [31]. Uterine pressures are mostly obtained by means of a closed special fluid-filled balloon catheter (as for rectal pressure). (See ESM addendum 12.)

Advantages and disadvantages (Table 1)

The major disadvantages of this technique are the same as for rectal pressures: i.e. it is more difficult, implicates more manipulation, is intermittent, and cannot be used on patients with gynaecological bleeding or infection. Since it is also fluid-filled it has all the problems associated with a hydrostatic fluid column, but is needle-free. Finally, this technique has not been validated in specific ICU patient populations. This technique has no clinical implications in the ICU setting.

## Inferior vena cava pressure

Description

The inferior vena cava pressure (IVCP) has been suggested as an estimation for IAP. Basically it uses the same techniques as described previously but applied to an IVC catheter. A normal central venous line is inserted into the inferior vena cava via the left or right femoral vein. The intra-abdominal position of the catheter is confirmed by portable lower abdomen X-ray, and confirmation of a rise in IAP following external abdominal pressure. A three-way stopcock is connected to the distal lumen, one end is connected to a pressure transducer via arterial tubing and the other end is connected to a pressurized infusion bag of 1,000 ml saline. The transducer is zeroed at the midaxillary line with the patient in the supine position and IAP is read end-expiratory as with CVP.

Advantages and disadvantages (Table 1)

The major disadvantage of this technique is the risk of (possible catheter-related) bloodstream infections and septic shock. The initial placement is more time-consuming. It has also the problems inherent to fluid-filled systems and poses potential injury to the patient and healthcare workers. The major advantages are that a continuous trend can be obtained, it does not interfere with urine output, and it could be used in bladder-trauma patients. Finally this technique has not been validated in specific ICU patient populations. In an animal study comparing different methods of indirect IAP measurement, Lacey and co-workers found a good correlation between bladder and inferior vena cava pressure with direct intraperitoneal IAP measurement, but not with gastric, femoral or rectal pressure [29]. Lee and co-workers also found a good correlation in 30 patients during laparoscopy [27]. A recent study in man, comparing superior vena cava pressure (SVCP) with common iliac venous pressure (CIVP) in various conditions of IAP and PEEP showed that the difference between CIVP and SVCP was not affected by the IAP, which implies that CIVP does not reflect IAP correctly [32]. The most likely explanation is the differing anatomy and experimental model used to induce increased IAP in canine studies. In humans both CVIP and SVCP increase as IAP increases [32]. Recently, Joynt and co-workers also found a good correlation between SVCP and IVCP regardless of IAH [33]. This technique has limited implications in the ICU setting.

## Microchip transducer-tipped catheters

Description

Different types of catheters tipped with microchip transducers are nowadays available on the market. They can either be placed via the rectal, uterine, vesical or gastric route. These catheters can either have a 360° membrane pressor sensor in the organ (rectum, uterus, bladder, stomach) connected to an external transducer in a reusable cable or they can have a fibre-optic in vivo pressure transducer in the tip of the catheter itself. These catheters provide true zero in-situ calibration. By disconnecting and checking for zero on the monitor, clinicians can instantly validate and check the zero status of the monitor and the transducer [31]. Recently, Schachtrupp and co-workers found a good correlation between IAP calculated be a piezoresistive pressure measurement and direct insufflator pressure ($R^2$=0.92), with a difference of 1.6±4.8 mmHg; however, the limits of agreement were large (−8 to 11.2 mmHg) [24]. This might have been due to an unknown measurement drift due to the fact that the device cannot be zeroed to the environment when placed intra-abdominally. (See ESM addendum 13.)

Advantages and disadvantages (Table 1)

The major disadvantages of this technique is that it is very expensive, with catheter-price ranging from €1,000 to €1,500. These catheters are said to be re-usable a couple of times after cleaning with soap and water and gas sterilisation, but no data on ICU patients are available. These catheters are mostly used during urodynamic studies and labour for a limited period of time (hours); none of them have been tested in ICU patients for longer periods of time (days to weeks). The major advantages are that a continuous trend can be obtained, it is less time-consuming, and it does not interfere with urine output. This technique has no clinical implications in the ICU setting.

## Reproducibility of IAP measurement

As stated previously, the intra-vesical route evolved as the gold standard. However, considerable variability in the measurement technique has been noted and the common pitfalls are briefly addressed below.

1. Malpositioning of the pressure transducer with regard to the symphysis pubis after repositioning of the patient. This may lead to over- and underestimation of IAP, which is commonly seen at changes of nurse shifts.
2. All fluid-filled systems connected to a pressure transducer have their own dynamic response properties

that can create distortions or artefacts in the IAP pressure waveform, leading to signal over- or under-damping [14, 15].

3. It is the most used and validated technique, but with inadequate accuracy and reproducibility. The inaccuracy can come from the presence of air-bubbles in any fluid-filled system leading to over- or underestimation. If the measurement itself is inaccurate, this also implies that it is not reproducible. However, when the pressure transducer position is consistently too high or too low with a fully compliant transducer system of high intrinsic resonant frequency the IAP value obtained will be too low or too high, respectively, but may be reproducible. In order to get an idea of these reproducibility problems with bladder pressure we performed a multicentre snapshot study (four IAP measurements each every 6 h) on a given day [4]. The mean IAP was 10.2±2.7 mmHg, (range 7.6±4 to 12.7±5.7). Analysis according to Bland and Altman showed a global bias of IAP within 24 h (difference between minimum and maximum value) of 5.1±3.8 (SD) mmHg (95% CI 4.3–5.9); the limits of agreement were −2.5 to 12.7 mmHg. The bias differed from centre to centre between 2.4 and 6.2 mmHg, with one outlier bias value as high as 11 mmHg, raising questions as to the reproducibility of the measurement technique used in that centre and making it difficult to compare literature data [4]. The mean coefficient of variation (defined as the standard deviation divided by the mean IAP) was 25%, which is comparable to daily fluctuations in other pressures, like central venous pressure or pulmonary artery occlusion pressure. However, this coefficient ranged from 4% to 66% between centres. Since the literature provides no data on 24-h continuous IAP-measurement in the ICU, it is not possible to determine whether these variations or fluctuations in IAP during one study day were normal or related to the measurement technique used.
4. The bladder "gold standard" measurement techniques reported are not uniform; most authors recommend to inject 50 ml [1, 2], others 0 ml [16], 100 ml [13, 23], 200 ml (data from internet: Brenda Morgan, Clinical Educator, CCTC on http://critcare.lhsc.on.ca/education/abdcompt.html, last revised 2001) or even 250 ml [17] of saline into the bladder. In fact, in the initial article from Iberti and co-workers, data are presented from a canine model without stating the volume instilled in the bladder. The only statement was that "the bladder was continuously emptied between measurements" [16]. In a following study, Iberti and co-workers presented human data stating, "using a sterile technique an average of 250 ml of normal saline was infused through the urinary catheter to gently fill the bladder and eliminate air in the drainage catheter" [17].
5. Conflicting results are reported in the literature regarding the validation of IVP versus directly measured IAP during laparoscopy. In a recent study, Yol and co-workers compared bladder pressure with direct insufflation pressure during laparoscopic cholecystectomy in 40 patients and he found a very good correlation between the two measurements ($R$=0.973, $P$<0.0001) [32]. This was also shown by Fusco and co-workers, who compared direct laparoscopic insufflation pressure with bladder pressures measured with bladder volumes of 0, 50, 150 and 200 ml [5]. He found that there was a good correlation across the IAP range from 0 to 25 mmHg between direct and indirect methods with all tested volumes. A bladder volume of 0 ml demonstrated the lowest bias, but when considering only elevated IAPs (25 mmHg) a bladder volume of 50 ml revealed the lowest bias. He concluded that intravesicular pressure closely approximates IAP and that instilling 50 ml of saline improved the accuracy of the bladder pressure in measuring elevated IAPs. However Johna and co-workers recently found that intravesicular pressure did not reflect actual intra-abdominal insufflation pressure (limited up to 15 mmHg) during laparoscopy [34]. He concluded that further research is needed to identify possible variables that may play a role in the relationship between the urinary bladder and abdominal cavity pressures, providing better means for diagnosing ACS. Further reading shows that the methodology of this study was poor.
6. Although many articles have validated IVP against direct insufflation pressures, it is difficult to extrapolate these single observer comparisons in patients undergoing general anesthesia and paralysis to a mixed ICU population of patients not under muscle relaxation as well as subject to other confounding factors (nurse shifts, position, zero reference, etc.). Direct IAP measurement via a laparoscopic insufflator is prone to errors by flow dynamics, resulting in rapid increases in pressure during insufflation. The Verres needle opening can be blocked by tissue or fluid leading to over- or underestimation of IAP and pressures can be influenced by muscle relaxation. Laparoscopy remains an artificial environment, this makes it even more difficult to validate indirect IAP measurement methods.
7. Baseline IAP and the volume instilled in the bladder are important. Gudmundsson and co-workers found recently in an animal study that the IAP increase by instilling Ringer's solution into the abdominal cavity correlated well with intra-vesical pressures [6]. It was also found that IVP as an estimation for IAP is affected by the amount of fluid in the bladder that should not exceed 10–15 ml. If the baseline IAP is lower than 8 mmHg, a 131-ml extra bladder volume is needed to increase IAP by 2 mmHg; however, if baseline IAP is 20 mmHg, only 39-ml extra bladder volume is needed for the same IAP increase [6]. We recently came to the same conclusions: by analysing bladder pressure

volume curves we found that IVP significantly increased depending on the volume instilled. The IVP rose from 4.2±3.2 mmHg at the baseline to 6.9±5 mm Hg with 50 ml and 23.7±16.1 at 300 ml ($P$<0.0001, ANOVA) [7]. If IVP is used as an estimate for IAP, the volume instilled in the bladder should be between 50 and 100 ml; however, in some patients with a low bladder compliance IVP can be raised at low bladder volumes. Ideally a bladder PV curve should be constructed for each individual patient before using IVP as an estimation for IAP. This study makes it difficult to compare the literature data. It raises not only questions with regard to the previously published definitions and IAP cut-offs, but it also puts the IVP in question as the so-called gold standard. Ideally the bladder should be fully emptied before an IAP measurement, but how can you be really sure?

8. Body position is important. Putting a patient in different body positions has significant effects on IAP (Fig. 10). This is in contradiction with the hypothesis that the abdominal compartment is primarily fluid in character and should follow the law of Pascal, since IAP would then remain constant regardless of body position as fluid is not compressible. The abdomen should in fact be looked at as a "fluidlike" compartment with different components that may influence IVP (the intrinsic weight of the organs, the presence of ascites, the air in the bowel, etc.). Assessment of IAP should, therefore, always be done in the complete supine position. The upright position significantly increases IAP compared with the supine. The effects on IAP being more pronounced in obese patients [35].

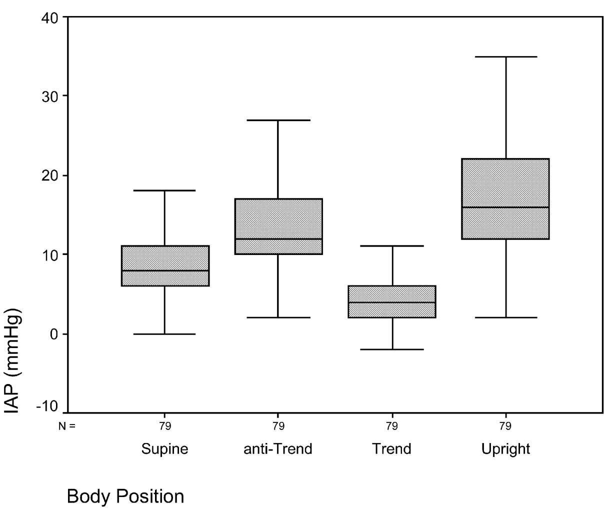



**Fig. 10** Boxplot of mean IAP values in different body positions. The IAP was significantly higher in the anti-Trendelenburg and upright position versus the supine, and significantly lower in the Trendelenburg position versus the supine ($P$<0.0001, one-way Anova)

Many of these drawbacks are not only true for the bladder but are also present when IAP is estimated via other routes. Not much has been studied on the effects of spontaneous breathing, mechanical ventilation, the presence of expiratory muscle activity, auto-PEEP, and curarisation on IAP measurement via the different routes.

Definitions for IAH and ACS stand or fall by the correct measurement of IAP and its reproducibility. Recent literature data put the bladder pressure in question as the so-called gold standard for abdominal pressure [5, 6, 34–36].

## Conclusion

This review has undertaken an analysis of the advantages and disadvantages, as well as a cost projection, for each IAP measurement technique and supports the view that: (1) there is no gold standard; (2) it is difficult to compare the different techniques; (3) cost-effectiveness is an issue; (4) IVP can be used as an estimation for IAP as a screening method to identify patients at risk via manometry; (5) IVP can be used as an estimation for IAP for initial follow-up either with the Cheatham or revised bladder technique; (6) for (multicentre) study purposes, surgical patients, trauma patients, patients at risk for IAH and difficult ICU patients, like mechanically ventilated patients with one or more other organ failures (assessed by SOFA score), it is preferable to switch to a continuous method for IAP monitoring via the stomach and focus therapy on optimising IAP and APP.

**Acknowledgements** I am indebted to my wife, Ms. Bieke Depré, for her patience, advice and technical assistance with the preparation of this manuscript, and to my three sons for providing a quiet writing environment. I also thank Dr. Rao Ivatury and Julia Wendon for their English editing of the manuscript. Part of this work was presented at: the 14th Annual Congress of the European Society of Intensive Care Medicine, Geneva, Switzerland, 30 September–3 October 2001; the 22nd International Symposium on Intensive Care and Emergency Medicine, Brussels, Belgium, 19–22 March 2002; the 13th Symposium Intensivmedizin and Intensivpflege, Bremen, Germany, 19–21 February 2003; the 23rd International Symposium on Intensive Care and Emergency Medicine, Brussels, Belgium, 18–21 March 2003; the 16th Annual Congress of the European Society of Intensive Care Medicine, Amsterdam, The Netherlands, 5–8 October 2003. This study was supported by Holtech Medical, Denmark (contact Bo Holte at holtech@email.dk). There was no financial support from Holtech other than making the product (Foleymanometer) available, free of charge. This study was supported by Ackrad Medical, USA (contact Charles Noto at cnoto@ackrad.com). There was no financial support from Ackrad other than making five oesophageal balloon catheters available, free of charge. This study was supported by Spiegelberg, Germany (contact Andreas Spiegelberg at info@spiegelberg.de). There was no financial support from Spiegelberg other than making the gastric balloon IAP-catheters and IAP-monitors available for study purposes, free of charge.

## References


1. Malbrain MLNG (2001) Intra-abdominal pressure in the Intensive Care Unit: clinical tool or toy? In: Vincent JL (ed) Yearbook of Intensive Care and Emergency Medicine. Springer, Berlin Heidelberg New York, pp 547–585
2. Malbrain MLNG (2002) Abdominal perfusion pressure as a prognostic marker in intra-abdominal hypertension. In: Vincent JL (ed) Yearbook of Intensive Care and Emergency Medicine. Springer, Berlin Heidelberg New York, pp 792–814
3. Pouliart N, Huyghens L (2002) An observational study on intraabdominal pressure in 125 critically ill patients. Crit Care 6 (Suppl 1):S3
4. Malbrain MLNG, for the CIAH study group (2001) Prevalence of intra-abdominal hypertension in the ICU. Intensive Care Med 27 (Suppl 2):S176
5. Fusco MA, Martin RS, Chang MC (2001) Estimation of intra-abdominal pressure by bladder pressure measurement: validity and methodology. J Trauma 50:297–302
6. Gudmundsson FF, Viste A, Gislason H, Svanes K (2002) Comparison of different methods for measuring intra-abdominal pressure. Intensive Care Med 28:509–514
7. Verbrugghe W, Van Mieghem N, Daelemans R, Lins R, Malbrain MLNG (2003) Estimating the optimal bladder volume for intra-abdominal pressure measurement by bladder pressure-volume curves. Critical Care 7(Suppl 2):P184
8. Van Mieghem N, Verbrugghe W, Daelemans R, Lins R, Malbrain MLNG (2003) Can abdominal perimeter be used as an accurate estimation of intra-abdominal pressure? Critical Care 7 (Suppl 2):P183
9. Kirkpatrick AW, Brenneman FD, McLean RF, Rapanos T (2000) Is clinical examination an accurate indicator of raised intra-abdominal pressure in critically injured patients? Can J Surg 43:207–211
10. Sugrue M, Bauman A, Jones F, Bishop G, Flabouris A, Parr M, Stewart A, Hillman K, Deane SA (2002) Clinical examination is an inaccurate predictor of intraabdominal pressure. World J Surg 26:1428–1431
11. Castillo M, Lis RJ, Ulrich H, Rivera G, Hanf C, Kvetan V (1998) Clinical estimate compared to intra-abdominal pressure measurement. Crit Care Med 26 (Suppl 1):78A
12. Platell CF, Hall J, Clarke G, Lawrence-Brown (1990) Intra-abdominal pressure and renal function after surgery to the abdominal aorta. Aust N Z J Surg 60:213–216
13. Kron JL, Harman PK, Nolan SP (1984) The measurement of intra-abdominal pressure as a criterion for abdominal re-exploration. Ann Surg 199:28–30
14. Darovic GO, Vanriper S, Vanriper J (1995) In: Darovic GO (Ed) Hemodynamic monitoring, 2nd edn. WB Saunders, Philadelphia, pp 149–175
15. Kleinman B, Powell S, Kumar P, Gardner RM (1992) The fast flush test measures the dynamic response of the entire blood pressure monitoring system. Anesthesiology 77:1215–1220
16. Iberti TJ, Kelly KM, Gentil DR, Hirsch S, Benjamin E (1987) A simple technique to accurately determine intra-abdominal pressure. Crit Care Med 15:1140–1142
17. Iberti TJ, Lieber CE, Benjamin E (1989) Determination of intra-abdominal pressure using a transurethral bladder catheter: clinical validation of the technique. Anesthesiology 70:47–50
18. Cheatham ML, Safcsak K (1998) Intraabdominal pressure : a revised method for measurement. J Am Coll Surg 186:594–595
19. Sagraves SG; Cheatham ML; Johnson JL; White M; Block EF; Nelson LD (1997) Intravesicular pressure monitoring does not increase the risk of urinary tract or systemic infection. Crit Care Med 27:A48
20. Collee GG, Lomax DM, Ferguson C, Hanson GC (1993) Bedside measurement of intra-abdominal pressure (IAP) via an indwelling naso-gastric tube: clinical validation of the technique. Intensive Care Med 19:478–480
21. Sugrue M, Buist MD, Lee A, Sanchez DJ, Hillman KM (1994) Intra-abdominal pressure measurement using a modified nasogastric tube: description and validation of a new technique. Intensive Care Med 20:588–590
22. Debaveye Y, Bertieaux S, Malbrain M (2000) Simultaneous measurement of intra-abdominal pressure and regional CO2 via a gastric tonometer. Intensive Care Med 26 (Suppl 3):S324
23. Malbrain MLNG (2003) Validation of a novel fully automated continuous method to measure intra-abdominal pressure (IAP). Intensive Care Med 29 (Suppl 1):S73
24. Schachtrupp A, Tons C, Fackeldey V, Hoer J, Reinges M, Schumpelick V (2003) Evaluation of two novel methods for the direct and continuous measurement of intra-abdominal pressure in a porcine model. Intensive Care Med 29:1605–1608
25. Cheatham ML, White MW, Sagraves SG, Johnson JL, Block EFJ (2000) Abdominal perfusion pressure: a superior parameter in the assessment of intra-abdominal hypertension. J Trauma 49:621–627
26. Harrahill M (1998) Intra-abdominal pressure monitoring. J Emerg Nurs 24:465–466
27. Lee SL, Anderson JT, Kraut EJ, Wisner DH, Wolfe BM (2002) A simplified approach to the diagnosis of elevated intra-abdominal pressure. J Trauma 52:1169–1172
28. Malbrain MLNG, Leonard M, Delmarcelle D (2002) A novel technique of intra-abdominal pressure measurement: validation of two prototypes. Crit Care 6 (Suppl 1):S2–S3
29. Lacey SR, Bruce J, Brooks SP, Griswald J, Ferguson W, Allen JE, Jewett TC, Karp MP, Cooney DR (1987) The relative merits of various methods of indirect measurement of intra-abdominal pressure as a guide to closure of abdominal wall defects. J Ped Surg 22:1207–1211
30. Shafik A, El-Sharkawy A, Sharaf WM (1997) Direct measurement of intra-abdominal pressure in various conditions. Eur J Surg 163:883–887
31. Dowdle M (1997) Evaluating a new intrauterine pressure catheter. J Reprod Med 42:506–513
32. Yol S, Kartal A, Tavli S, Tatkan Y (1998) Is urinary bladder pressure a sensitive indicator of intra-abdominal pressure? Endoscopy 30:778–780
33. Joynt GM, Gomersall CD, Buckley TA, Oh TE, Young RJ, Freebairn RC (1996) Comparison of intrathoracic and intra-abdominal measurements of central venous pressure. Lancet 347:1155–1157
34. Johna S, Taylor E, Brown C, Zimmerman G (1999) Abdominal compartment syndrome: does intra-cystic pressure reflect actual intra-abdominal pressure? A prospective study in surgical patients. Crit Care 3:135–138
35. Malbrain MLNG, Van Mieghem BN, Verbrugghe W, Daelemans R, Lins R (2003) Effects of different body positions on intra-abdominal pressure and dynamic respiratory compliance. Crit Care 7 (Suppl 2):P179
36. Malbrain MLNG (1999) Abdominal pressure in the critically ill: measurement and clinical relevance. Intensive Care Med 25:1453–1458