TITLE: Non-invasive measurement of intra-abdominal pressure by assessment of abdominal wall tension

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FOOTNOTE TO THE TITLE	in vitro and in vivo studies
RUNNING TITLE	Abdominal wall tension (AWT) measurement and IAP
SUBJECT CATEGORY	Shock/Sepsis/Trauma/Critical Care
SOURCES OF FUNDING	No funding was received for this study
PREVIOUS COMMUNICATION	2009 World Congress of Abdominal Compartment Syndrome, June 25-27, Dublin, Ireland.
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ABSTRACT

Background: Sustained increased intra-abdominal pressure (IAP) has negative effects. Non-invasive IAP measurement is beneficial with regard to patient safety and in patients in whom invasive IAP-measurements are unreliable. We assessed the relation between IAP and abdominal wall tension (AWT) in vitro and in vivo.

Materials and methods: The abdomens of 14 corpses were insufflated with air. IAP was measured at intervals up to 20 mmHg. At each interval, AWT was measured five times at six points. In 42 volunteers, AWT was measured at five points in supine, sitting and standing positions during various respiratory manoeuvres. Series were repeated in 14 volunteers to measure reproducibility by calculating coefficients of variation (CV). ANOVA was used for analyses.

Results: In corpses, all points showed significant correlations between IAP and AWT ($p<0.001$ for points 1-4 in the upper abdomen, $p=0.017$ for point 5 and $p= 0.008$ for point 6 in the lower abdomen). Mean slopes were greatest at points across the epigastric region (points 1-3). In vivo measurements showed that AWT was on average 31% higher in men compared to women ($p<0.001$), and increased from expiration to inspiration to Valsalva's manoeuvre (all $p<0.001$). AWT was highest at points 1 and 2 and in standing position, followed by supine and sitting positions. BMI did not influence AWT ($p=0.77$). Mean CV of repeated measurements was 14%.

Conclusions: AWT reflects IAP. The epigastric region appears most suitable for AWT measurements. Further longitudinal clinical studies are needed to assess usefulness of AWT measurements for monitoring of IAP.

KEY WORDS: intra abdominal pressure, abdominal wall tension, abdominal hypertension, compartment syndrome, measurement, non-invasive, surgery, trauma, complications, bladder pressure

INTRODUCTION

Intra-abdominal hypertension (IAH) is a condition in which intra-abdominal pressure (IAP) is consistently raised over 12 mmHg. IAH can lead to the development of the abdominal compartment syndrome (ACS), which has been recognized as a significant cause of morbidity and mortality in Intensive Care Unit (ICU) patients [1, 2]. IAH occurs in approximately 50% of the populations of general specialized adult Intensive Care Units [3, 4]. Raised IAP (over 20 mmHg) causes severe organ dysfunction and leads to a vicious circle, resulting into multiple organ failure, and finally, death [2, 3, 5-7]. In case of ACS, these serious complications can only be averted by surgical decompression if conservative medical treatment has failed [8]. Early diagnosis is therefore essential for adequate intervention and damage control.

Abdominal wall tension (AWT) has been considered a possible predictor for the development of acute pancreatitis, since abdominal hypertension has been reported as a marker of severity of the disease [9, 10]. Finally, authors of several studies on abdominal hernias and on incisional hernias in particular, have considered AWT as one of the possible factors involved in the development of abdominal hernias [11-13].

IAP can by estimated by performing measurements via the bladder, but also via uterus, rectum and stomach [14]. The intravesical pressure measurement using a Foley catheter has been validated and has remained the accepted gold standard measurement of IAP for clinical use. This measurement, however, can be unreliable in case of low intrinsic bladder compliance, bladder trauma or pelvic haematoma, which may compress the bladder. Also, a significant risk of urinary tract infection is associated with placement of a urinary catheter.

With the increase of IAP, the abdomen expands, acting like a balloon. This expansion results in increase of abdominal wall tension (AWT), and is directly correlated with IAP. A previous study in two fresh human corpses has shown that a relationship exists between AWT and IAP [15]. Non-invasive measurement of IAP, if feasible, could be useful for fast , easy, cheap and patient friendly screening and monitoring of patients at risk of developing IAH and ACS in whom intravesical measurements are unreliable or undesired for other reasons. In order to be able to assess the relationship between AWT and IAP more precisely, we performed measurements in a larger group of fresh human corpses. We also obtained AWT values in healthy volunteers during a variety of physiological actions, similar to the studies performed by Iqbal *et al.* and Cobb *et al.* [16, 17]. In the latter study, normal range values for IAP in healthy subjects were measured during typical activities of daily life, e.g. in supine position, standing, sitting and whilst performing an abdominal crunch [17].

MATERIALS AND METHODS

The prototype used for measuring AWT consisted of a built-in force and distance sensor, attached to a handheld personal digital assistant (PDA, HP IPAQ) (Figure 1). This device can measure the amount of force (N) needed to indent a certain distance (mm), which is then visualized on the PDA in graphics. Thereafter, a line is fitted by means of method of least squares and the resulting slope (RC) of this line is expressed in N/mm as previously described [15].

Human corpses

Fresh human corpses (up to one week post-mortem and adequately cooled) were included in this study. Exclusion criteria were visible abdominal scars (indicative of prior abdominal surgery) or signs of tissue necrosis (suggesting progressed stages of decay). Six points, derived from anatomical structures, were marked on each abdominal wall: 5 cm caudal to the xiphoid bone (point 1), 5 cm cranial to the umbilicus (point 2), 5 cm left to point 2 (point 3), 10 cm left to point 2 (point 4), 5 cm cranial to the pubic bone (point 5) and an extra point, 5 cm left to point 5 (point 6) (Figure 1). The abdomens were then insufflated with air by means of a laparoscopic set-up, using a Veress needle. IAP was increased and measured at intervals of 5mmHg up to 20mmHg. At each interval, achieved IAP was noted and AWT was measured five times at each of the marked points. The mean value of these five measurements was used in analyses. Pressures below 4 mmHg were considered to represent inadequate abdominal insufflation and were excluded from analyses. Repeated measurements ANOVA was used to assess relations between mean values of measured tensions per point versus achieved IAPs, points of measurement and subjects.

Healthy volunteers

Healthy students were asked to volunteer for the in vivo study. Procedures were followed in accordance with the ethical standards of the medical ethics committee at our institution. Exclusion criteria were history of abdominal surgery and current or past pregnancy. Gender (male, female), height (m), weight (kg) and waist (cm) were measured in each subject and body mass index (BMI) was calculated. It was attempted to recrute students from all ranges of BMI. The first five points as described in the section ‘human corpses’ were marked on the abdomen as shown in figure 2.

Short series of test measurements were performed to familiarize subjects with the measurement technique. For the actual series, subjects were first measured in supine position during late expiration, inspiration and Valsalva manoeuvre (straining against a closed epiglottis). During each respiratory movement, measurements were performed on the five points mentioned above. Measurements were repeated in sitting and standing positions and the order was kept identical for each subject. This resulted in 15 measurements in each position (five for each respiratory movement) and a total of 45 measurements in each subject. In 14 volunteers the entire series were repeated in order to measure reproducibility of measurements by calculating coefficients of variation (CV). Repeated measurements ANOVA were used to assess relations between measured AWT and other variables (respiratory manoeuvre, gender, BMI and position). In these analyses, RCs were transformed logarithmically in order to obtain approximate normal distributions. Two-sided p-values below 0.05 were considered significant in all analyses.

RESULTS

The abdomens of 14 human corpses (8 female, 6 male, mean age 83 years at death) were insufflated with air after a mean period of two days after death (range 1-6 days). Point 4 could not be measured in 6 subjects due to anatomic variations, with the rib cage impeding measurements. At all points of measurement, significant correlations were found between IAP and AWT. Mean slopes were greater at points across the epigastric region (points 1-3) than slopes at other points (Table 1). Considerable variations were present between individual subjects regarding the slopes and the levels of measurement, as illustrated in Figure 3 for anatomical point 1.

In vivo measurements were performed in 42 students (22 females, 20 males) aged between 18-28 years with a mean BMI of 22,7 kg/m^2 (range 16,9-28,1 kg/m^2). Two points could not be measured in all volunteers. Point 1 was omitted in 1 subject due to a long xyphoid process and point 4 could not be measured in 8 volunteers due to anatomic variations, with underlying rib cages impeding measurements. The reproducibility part of the study resulted in a mean CV of the two repeated measurements of 14% (10th-90th percentiles: 2%-29%).

In men, compared to women, AWT levels were on average 31% higher (95% CI 13%-52%; $p<0.0001$). BMI did not significantly influence levels of AWT ($p=0.77$). AWT levels increased significantly from late expiration to inspiration to Valsalva's manoeuvre (all $p<0.001$). ANOVA showed that AWT was significantly higher at points 1 and 2 compared to other points (all $p<0.001$) but no significant difference was found between points 1 and 2 ($p=0.403$). AWT leves were highest in standing position, followed by supine and sitting position (geometric means 1.36, 1.18 and 1.06 N/mm, respectively). The results for supine position are shown in Figure 4 according to point of measurement and respiratory manoeuvre.

DISCUSSION

These series of systematic, controled measurements in human corpses and healthy volunteers are the first to show correlations between IAP and AWT on a larger scale. Changes in IAP lead to changes in AWT and have proven to differ between points across the abdominal wall, which is a new finding. Variations in AWT levels across the abdominal surface could explained by anatomical differences in muscle and tendon structures. Our studies in healthy volunteers have demonstrated the correlation between respiratory manoeuvres of daily life, reflective of IAP, and AWT. Additional information from these series include the observation that gender is of influence on the measured levels of AWT. We suspect that the physique of the male abdomen is associated with a lower compliance of the abdominal wall and thereby, leads to higher levels of AWT. This relative high stiffness (i.e., high value of RC) of the male abdominal wall has previously been reported by Song *et al.* [18], who also observed that the abdominal wall is stiffer in the transverse plane than the sagittal plane. BMI and IAP were found to be significantly correlated in standing position with and without Valsalva manoeuvre by Cobb *et al.* [17]. Although no influence of BMI on the levels of AWT was found in our study, we doubt that the range of BMI in our population was wide enough to conclude that no such influence exists. Especially if the layer of subcutaneous fat tissue outmeasures the maximum distance which can be indented by the measuring device, we hypothesize that this could have substantial influence on measured levels of AWT. Studies in larger populations with wide ranges of BMI are required to substantiate this hypothesis with evidence.

The experiments in human corpses have provided us with data on AWT for IAP up to 20 mmHg. AWT could not be measured over 20mmHg. It was observed that high IAP led to production of urine and regurgition of gastric content from 15 mmHg upwards. The limited availability of eligible fresh human corpses restricts the possibility of performing tests in larger series. We therefore feel that the precise influence of variables of interest on AWT levels are preferably performed in healthy volunteers or patients.

Future studies on AWT measurements should preferably be combined with IAP measurements in volunteers or in patients with Foley catheters already in place. Points 1 and 2 were found most suitable for detection of changes in IAP and AWT due to the high slopes. These measurements may not be possible to perform in patients with upper midline incisions. Point 4 could not be measured in a large proportion of volunteers, which makes this point less usable as a clinical reference point. Point 6 was not measured in volunteers since this point was found to have the smallest slope in human corpses and was considered least suitable for AWT measurements, with increases in IAP resulting in relatively small changes in AWT.

Improvements to the measuring device include technical aspects, such as an increased repeatibility of measurements, and practical aspects, such as the ability of sterilisation of the device. This would expand the range of possible clinical studies in operating rooms, and guarantee patient safety during surgery. Future clinical studies should include longitudinal measurements, since a considerable variation in slopes and levels of measurement were found between individuals. Besides comparison to other methods of IAP measurements, including the standard intravesical method, the influence of sedation and muscle relaxants on AWT, as widely used in Intensive Care Units, should be investigated. Measurement of AWT is relatively easy and could be performed by nurses without the requirement of a long period of training or supervision. This would benefit both patients and daily practice of nurses. AWT may prove an interesting new method to measure IAP non-invasively and might lead to earlier diagnosis of clinical signs of IAH and timely intervention.

Acknowledgements

We greatly appreciate the assistance and input provided by N.A. Agudelo, M. Verwaal, S. van Belle, J. van Ophemert, Y. van Steinvoort and J. Jeekel.

REFERENCES

1. Moore AFK, Hargest R, Martin M, Delicata RJ. Intra-abdominal hypertension and the abdominal compartment syndrome. Br J Surg 2004; 91:1102-1110.

2. Cheatham ML, Malbrain MLNG, Kirkpatrick A, Sugrue M, Parr M, De Waele J, Balogh Z, Leppäniemi A, Olvera C, Ivatury R, D'Amours S, Wendon J, Hillman K, Wilmer A. Results from the International Conference of Experts on Intra-abdominal Hypertension and Abdominal Compartment Syndrome. II. Recommendations. Intensive Care Med 2007;33:951-962.

3. Chen H, Li F, Sun JB, Jia JG. Abdominal compartment syndrome in patients with severe acute pancreatitis in early stage. World J Gastroenterol 2008;14:3541-3548.

4. Malbrain MLNG, Chiumello D, Pelosi P, Wilmer A, Brienza N, Malcangi V, Bihari D, Innes R, Cohen J, Singer P, Japiassu A, Kurtop E, De Keulenaer BL, Daelemans R, Del Turco M, Cosimini P, Ranieri M, Jacquet L, Laterre PF, Gattinoni L. Prevalence of intra-abdominal hypertension in critically ill patients: a multicentre epidemiological study. Intensive Care Med 2004;30:822-829.

5. Sugrue M, Jones F, Deane SA, Bishop G, Bauman A, Hillman K. Intra-abdominal hypertension is an independent cause of postoperative renal impairment. Arch Surg 1999;134:1082-1085.

6. Sugrue M, Balogh Z, Malbrain M. Intra-abdominal hypertension and renal failure. ANZ J Surg 2004;74:78.

7. Malbrain MLNG, Chiumello D, Pelosi P, Bihari D, Innes R, Ranieri VM, Del Turco M, Wilmer A, Brienze N, Malcangi V, Cohen J, Japiassu A, De Keulenaer BL, Daelemans R, Jacquet L, Laterre PF, Frank G, De Souza P, Cesana B, Gattiononi L. Incidence and prognosis of intraabdominal hypertension in a mixed population of critically ill patients: a multiple center epidemiological study. Crit Care Med 2005;33:315-322.

8. Meldrum DR, Moore FA, Moore EE, Franciose RJ, Sauaia A, Burch JM. Prospective characterization and selective management of the abdominal compartment syndrome. Am J Surg 1997; 174:667-673.

9. Pupelis G, Austrums E, Snippe K, Berzins M.Clinical significance of increased intraabdominal pressure in severe acute pancreatitis. Acta Chir Belg 2002;102:71-74.

10. Rosas JM, Soto SN, Aracil JS, Cladera PR, Borlan RH, Sanchez AV, Ros FB, Posa LG. Intra-abdominal pressure as a marker of severity in acute pancreatitis. Surgery 2007;141:173-178.

11. Park AE, Roth JS, Kavic SM. Abdominal wall hernia. Curr Probl Surg 2006; 43:326-332.

12. Ammaturo C, Bassi G. The ratio between anterior abdominal wall surface/wall defect surface. A new parameter to classify abdominal incisional hernias. Hernia 2005;9:316-321.

13. Junge K, Klinge U, Prescher A, Giboni P, Niewiera M, Schumpelick V. Elasticity of the anterior abdominal wall and impact for reparation of incisional hernias using mesh implants. Hernia 2001; 5:113-118.

14. Turnbull D, Webber S, Hamnegard CH, Mills GH. Intra-abdominal pressure measurement: validation of intragastric pressure as a measure of intra-abdominal pressure. Br J Anaesthesia 2007; 98:628-634.

15. Van Ramshorst GH, Lange JF, Goossens RHM, Agudelo NL, Kleinrensink GJ, Verwaal M, Flipsen SFJ, Hop WCJ, Wauben LSGL, Jeekel J. Non-invasive measurement of intra-abdominal pressure: a preliminary study. Physiol Meas 2008;29:N41-47.

16. Iqbal A, Haider M, Stadlhuber RJ, Karu A, Corkill S, Filipi CJ. A study of intragastric and intravesicular pressure changes during rest, coughing, weight lifting, retching, and vomiting. Surg Endosc 2008;22:2571-2575.

17. Cobb WS, Burns JM, Kercher KW, Matthews BD, Norton HJ, Heniford BT. Normal intraabdominal pressure in healthy adults. J Surg Res 2005;129:231-235.

18. Song C, Alijani A, Frank T, Hanna G, Cuschieri A. Elasticity of the living abdominal wall in laparoscopic surgery. J Biomechanics 2006;39:587-591.

TABLE 1

Summary of mean regression lines at anatomical points of measurement

		Mean regression lines			
Point	No of measurements	Mean intercept (N/mm)[a]	Slope (N/mm/mmHg)[a]	Standard error of mean slope	*P* value
1	289	1.61 (0.65)	0.079 (0.057)	0.015	<0.001
2	290	1.88 (0.87)	0.063 (0.030)	0.008	<0.001
3	268	1.75 (0.80)	0.066 (0.046)	0.013	<0.001
4	164	1.58 (0.96)	0.050 (0.027)	0.009	<0.001
5	289	1.58 (0.68)	0.033 (0.046)	0.012	0.017
6	290	1.36 (0.73)	0.041 (0.050)	0.013	0.008

[a] Data in parenthesis represent standard deviations of individual outcomes.

Fig. 1. Device for AWT measurements

patientnummer: 106
naam: vd berg
geb. datum: 04-06-1956 M/V: M

Fig. 2. Points of measurement across the abdominal wall

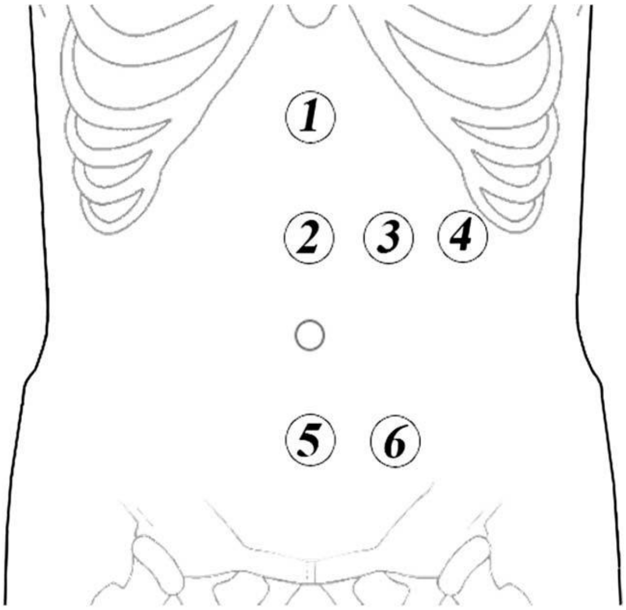

Fig. 3. Typical variations in levels of measurements and slopes of fitted regression lines at 5 cm below the xiphoid process (point 1). The separate 14 subjects are represented by different symbols and the individual regression lines are plotted. The median R-squared of the regression lines was 0.82 (range 0.02-0.97).

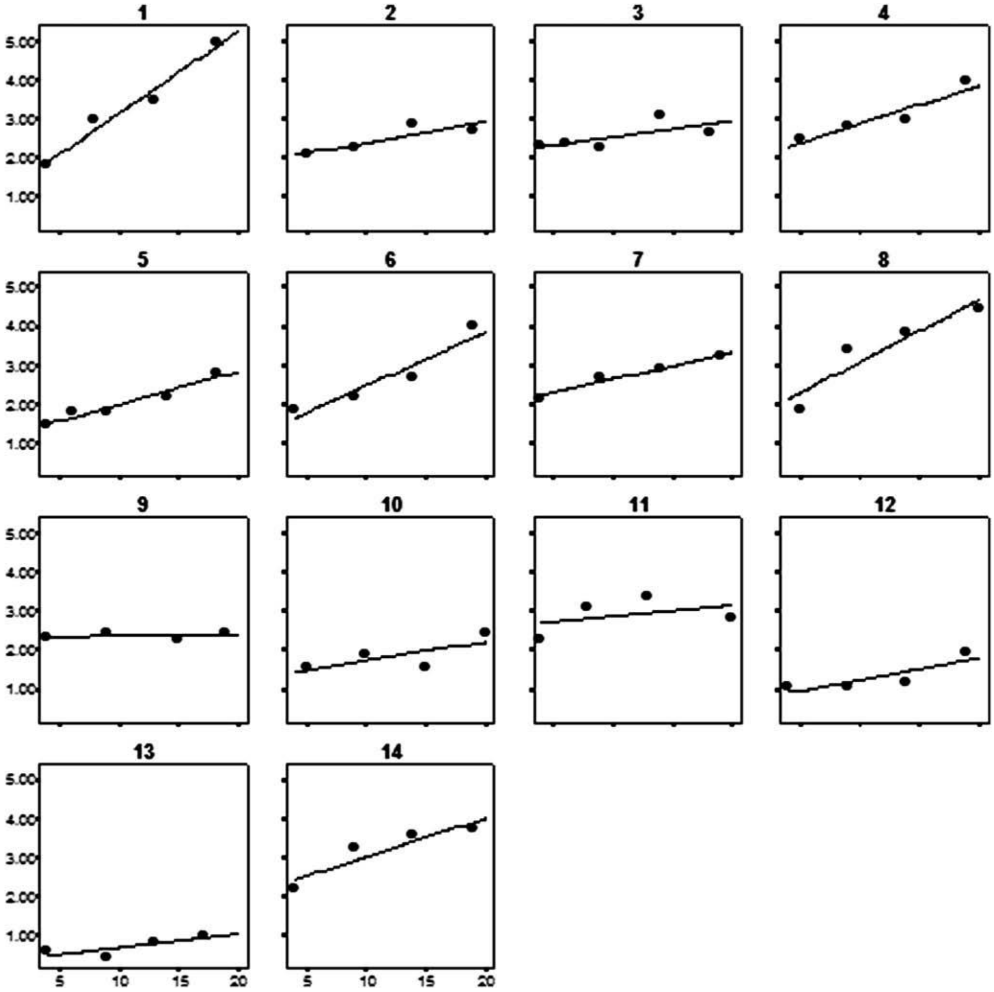

Fig. 4. Geometric mean RCs for supine position according to point of measurement. Error bars represent 95% confidence limits. Triangles: Valsalva manoeuver. Circles: inspiration. Squares: expiration