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Effects of prolonged increased intra-abdominal pressure on gastrointestinal blood flow in pigs

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Abstract
Background: The aim of the study was to investigate the effects of prolonged intra-abdominal pressure on systemic hemodynamics and gastrointestinal blood circulation.
Methods: The intra-abdominal pressure in anesthetized pigs was elevated to 20 mmHg (7 animals), 30 mmHg (7 animals), and 40 mmHg (4 animals), respectively. These pressures were maintained for 3 h by intra-abdominal infusion of Ringer's solution. A control group of seven animals had normal intra-abdominal pressure (IAP). Transit time flowmetry and colored microspheres were used to measure blood flow.
Results: An IAP of 20 mmHg did not cause significant changes in systemic hemodynamics or tissue blood flow. An IAP of 30 mmHg caused reduced blood flow in the portal vein, gastric mucosa, small bowel mucosa, pancreas, spleen, and liver. Serum lactate increased in animals with an IAP of 30 mmHg, but microscopy did not disclose mucosal damage in the stomach or small bowel. An IAP of 40 mmHg was followed by severe circulatory changes.
Conclusions: Prolonged IAP at 20 mmHg did not cause changes in general hemodynamics or gastrointestinal blood flow. Prolonged IAP at 30 mmHg caused reduced portal venous blood flow and reduced tissue flow in various abdominal organs, but no mucosal injury. A prolonged IAP of 40 mmHg represented a dangerous trauma to the animals.

Key words: Abdominal compartment syndrome — Cardiovascular physiology — Colon — Hemodynamics — Liver — Microspheres — Pancreas — Regional blood flow — Small bowel — Spleen — Stomach — Swine

Increased intra-abdominal pressure (IAP) is a clinical condition that has gained increased attention in recent years. Various diseases such as ruptured aortic aneurysm, necrotizing pancreatitis, small bowel obstruction, and abdominal trauma may be associated with IAP. Increased pressure can affect the blood perfusion of intra-abdominal organs, resulting in adverse pathophysiologic changes affecting several organ systems, especially the cardiovascular, renal, intestinal, and pulmonary systems.

With the development in laparoscopic surgery in recent years, larger and more time-consuming abdominal operations are performed laparoscopically, in which intra-abdominal pressure is maintained at 15 mmHg for 3 hours or more. A number of reported experimental studies have analyzed the effect of stepwise IAP increases reaching 30 to 40 mmHg over rather short periods [3, 5, 6]. These studies show that increased IAP reduces blood flow in gastrointestinal organs and in cardiac output.

It is well known that gastrointestinal organs can tolerate and withstand hypoperfusion and ischemia of short duration. However, the situation may be quite different if the IAP is kept elevated for long periods. As far as we know, the effects of prolonged elevated IAP on blood circulation in gastrointestinal organs have not been reported.

In the current study, the effects of prolonged increased IAP on central hemodynamics, gastrointestinal blood flow, and gastrointestinal morphology were examined. Intra-abdominal pressures of 20 to 40 mmHg were chosen, because 20 mmHg represents the upper limit for clinical laparoscopy, and 30 to 40 mmHg may be found with intra-abdominal hypertension under clinical conditions.

Material and methods

Anesthesia

The Norwegian Ethics Committee on Animal Research approved the experimental protocol, in which 25 domestic pigs, 30 ± 5 kg, were deprived of food overnight and premedicated with intramuscular atropine 1 mg, diazepam 10 mg, and ketamine 300 mg. After induction with isoflurane using a mask, the animals were orotracheally intubated and mechanically ventilated (Cato, Dräger, Lübeck, Germany). The aim was an end-tidal partial pressure of carbon dioxide (pCO_2) concentration of 3.5 to 6.0 kPa. The fraction of inspired oxygen (FiO2) was adjusted to maintain pulsoxy-

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metry saturation above 98%. Anesthesia was maintained with isoflurane (end-tidal volume concentration below 1.7%) together with intravenous (IV) infusion of fentanyl (~8 μg/kg/h) and midazolam (~0.5 mg/kg/h). Rectal temperature was kept between 38°C and 40°C with a heating pad.

Animal preparation

Acetated Ringer's solution was infused intravenously (IV) in amounts of 30 ml/kg/h. A Venflon 2 IV (outer diameter [OD] 1.0) was inserted into the femoral artery and connected to a SensoNor 840 pressure transducer (SensoNor, Norway) for measurement of arterial blood pressure and heart rate. A Portex catheter (OD, 1.34 mm) connected to the same type of transducer was inserted into the superior caval vein for measurement of central vein pressure. Another Portex catheter (OD, 1.34 mm) was inserted via the right carotid artery into the left cardiac ventricle for injection of microspheres, and the correct position was ensured by obtaining a typical pressure trace with low diastolic pressure.

A midline laparotomy was performed. A transit time flow probe (inner diameter [ID], 10 mm) was placed around the portal vein just distally to the division into the right and left hepatic branches, and the blood flow was measured by transit time flowmetry (Transonic Systems Inc., HT107, New York, USA). The left renal vein was cannulated via the inferior caval vein for collection of blood samples and measurement of pressure. In some animals, a cannula was placed into the portal vein for continuous measurement of portal vein pressure.

A double-lumen catheter was passed through the abdominal wall, placed in the right upper quadrant (above the liver), and connected to a pressure transducer (SensoNor 840) for continuous recording of the intra-abdominal pressure, and for infusion of Ringer's acetate into the peritoneal cavity to increase the intra-abdominal pressure. The abdominal incision then was closed.

Experimental protocol

After allowing 15 min of stabilization after surgery, baseline recordings were made and noted for 60 min. At the end of the stabilization period, the first microsphere injection was performed, together with notation of pressures and flow variables (baseline). Then Ringer's acetate was infused into the abdominal cavity until the intra-abdominal pressure had reached a level of 20 mmHg ($n = 7$), 30 mmHg ($n = 7$), or 40 mmHg ($n = 4$) respectively, in three groups of animals. A fourth group without infusion ($n = 7$) served as controls subjects. After 90 and 180 min of increased IAP, the second and third microsphere injections were performed, together with notation of pressures and flow variables with corresponding registrations in control subjects. Approximately 6 to 8 l of Ringer's acetate were infused during an experiment, and a similar amount was withdrawn after 180 min of increased IAP. Then 40 min after normalization of the intra-abdominal pressure, the fourth microsphere injection was performed, together with notation of pressures and flow variables. Finally, the animals were killed by an intracardiac injection of saturated potassium chloride.

Microspheres

Colored microspheres (Dye Trak, Triton Technology, San Diego, CA, USA) with a diameter of 15 μm were used to measure regional tissue blood flow and cardiac output (CO). These microspheres were surface coated with red, yellow, violet, or blue. For each experiment the sequence of the four types of colored spheres were randomized. Microspheres were injected (11.5×10^6 for red and yellow, 15×10^6 for violet and blue) into the left ventricle for 20 s followed by flushing of the catheter with 10 ml of saline. During microsphere injections and for 100 s afterward, an arterial reference blood sample was withdrawn from the right femoral artery with a constant-rate extraction pump (10 ml/min).

After the animals were killed, tissue samples were selected from various abdominal organs, weighed, and dissolved overnight in 15 ml of 4 mol/l potassium hydroxide with 0.05% Tween 80 at 60°C. The reference blood samples were treated the same as the tissue samples. The samples were filtered in a vacuum through 25-mm 10-μm-pore filters (Mitex® Membrane Filters, Ireland). The microspheres were washed with 0.05% Tween 80 and then with ethanol. The filters with their retained microspheres were centrifuged with 700 μl of dimethylforamide to elute the dyes. The solution of mixed dyes was scanned photometrically from 350 to 750 nm (Diode Array Spectrophotometer, Hewlett Packard 8452 A). The complex spectra obtained were resolved into their individual components and quantified using partial least squares multicomponent analysis on commercial software (Advanced Chemstation Software, Hewlett Packard). Tissue blood flow expressed as ml/min/g and cardiac output were computed according to standard formula, as previously described [10].

Vascular resistance across the vascular bed in the systemic and gastrointestinal circulation was determined according to the formula Pa-Pv/F, where Pa is the systemic arterial pressure, Pv is the pressure in the caval or portal vein, and F is cardiac output or portal vein blood flow.

Microscopy

Whole-wall samples of the antrum and corpus of the stomach and the small bowel were fixed in Bouin solution for 48 h. The specimens were further processed, cut into sections 5 μm thick and stained with hematoxylin and eosin (H&E). Histologic examination was undertaken after completion of all experiments. The tissue sections were coded so that the examiner was unaware of the experimental group to which they belonged. Conventional light microscopy was used for histologic examination. A total of 60 sections were studied.

Lactate

The lactic acid was determined at the Haukeland Hospital laboratory of clinical biochemistry by a modification of the Marbach and Weil [15] method, which was performed by aca® IV Discrete Clinical Analyzer nr LA 16.

Hematocrit

Hematocrit was determined using blood samples taken from the femoral artery (Blood Micro System 3Mk2; Radiometer, Copenhagen, Denmark).

Stastistical analysis

Unless otherwise noted, results are expressed as mean ± standard error of mean (SEM). Data for the experimental group with an increase of IAP to 40 mmHg and pressure and data sampled after 45 min of normalized IAP are purely descriptive (see later). Two-way analysis of variance (ANOVA) for repeated measures was used on baseline, 90-min, and 180-min data, with increased IAP as a repeated factor, and with 0 mmHg, 20 mmHg, and 30 mmHg as a grouping factor. When a significant interaction effect was found for the ANOVA, tests for simple main effects were performed [20]. Whenever justified by these analyses, post hoc Newman-Keuls tests for multiple contrasts were performed. Except for a significant interaction effect ($p < 0.10$), a p value less than 0.05 was regarded as statistically significant.

Results

Central hemodynamics

In control animals the cardiac output, heart rate, and arterial and venous blood pressures (Table 1) remained fairly constant throughout the experiment, as did portal vein blood flow (Fig. 1). In the group with IAP kept at 20 mmHg, no significant changes were found in these hemodynamic parameters. An IAP of 30 mmHg caused no significant changes in heart rate or arterial pressure. The mean CO decreased, but the change was not statistically significant. The superior caval vein pressure increased significantly ($p < 0.001$) at 30 mmHg IAP.

Table 1. Central hemodynamic variables in three groups of domestic swine with different intra-abdominal pressures

Intra-abdominal pressure (IAP) (mm Hg)	Baseline	Increased IAP		End of experiment[a]	ANOVA (–10, 90, and 180 min)
		90 min	180 min		
Cardiac output (l/min)					
0 (n = 7)	4.9 ± 0.5	4.3 ± 0.5	4.6 ± 0.7	4.2 ± 0.3	Pb: NS
20 (n = 7)	5.1 ± 0.4	4.9 ± 0.5	5.1 ± 0.9	5.6 ± 1.7	Pw: NS
30 (n = 7)	5.4 ± 0.4	4.2 ± 0.5	3.7 ± 0.6	5.3 ± 0.5	Pi: NS
Heart rate (beats/min)					
0 (n = 7)	145 ± 8	135 ± 9	139 ± 12	141 ± 14	Pb: NS
20 (n = 7)	117 ± 6	118 ± 4	121 ± 4	127 ± 6	Pw: NS
30 (n = 7)	131 ± 4	136 ± 8	141 ± 12	132 ± 7	Pi: NS
Mean arterial pressure (mmHg)					
0 (n = 7)	69 ± 3	72 ± 2	71 ± 3	70 ± 3	Pb: NS
20 (n = 7)	68 ± 1	69 ± 3	72 ± 1	64 ± 3	Pw: NS
30 (n = 7)	67 ± 3	69 ± 3	65 ± 4	53 ± 4	Pi: NS
Superior caval vein pressure (mmHg)					
0 (n = 7)	10 ± 1	10 ± 1	10 ± 1	10 ± 1	Pb < 0.001
20 (n = 7)	11 ± 1	12 ± 1	13 ± 1	11 ± 1	Pw < 0.005
30 (n = 7)	14 ± 2	18 ± 1[b]	20 ± 1[b]	15 ± 1	Pi = 0.01

[a] 40 min after normalization of IAP
[b] Different from baseline within group
Pb, Pw, and Pi are the probabilities by ANOVA for differences between groups, within groups, and of interaction, respectively
ANOVA, analysis of variance; NS, not significant

The portal vein pressure showed about the same values as the corresponding intra-abdominal pressures. It remained at baseline level in the control group. When the IAP was elevated to 20 mmHg or 30 mmHg, the portal vein pressure increased to the same levels.

Gastrointestinal blood flow

As shown in Fig. 1, the portal vein blood flow showed a significant decrease with time in all the experimental groups, most markedly in the animals with an IAP of 30 mmHg. The gastric mucosal blood flow remained rather constant in the control group. An increase in IAP to 20 mmHg did not influence the blood flow significantly. However, the gastric mucosal blood flow was decreased markedly after 90 min and 180 min at an IAP of 30 mmHg ($p < 0.025$ and $p < 0.01$, respectively).

In the small bowel mucosa, an initial significant reduction in blood flow occurred when the IAP was increased to 30 mmHg ($p < 0.005$). However, at 90 and 180 min, no significant effect of increased IAP could be observed.

As shown in Table 2, tissue blood flow in the gastric muscularis, gall bladder, and colon were not significantly influenced by changes in IAP. Blood flow in the small bowel muscularis decreased significantly during the first 90 min of the experiment in all the groups ($p = 0.001$). At 90 and 180 min, the blood flow was reduced markedly in the group with an IAP of 30 mmHg, as compared with the control group ($p < 0.005$).

An increase in IAP to 20 mmHg did not significantly influence blood flow in the pancreas, spleen, and liver (Fig. 2). On the other hand, the blood flow in these organs decreased markedly at an IAP of 30 mmHg. At 90 and 180 min, the flow values differed significantly from the corresponding flow values of the control group ($p = 0.025$–

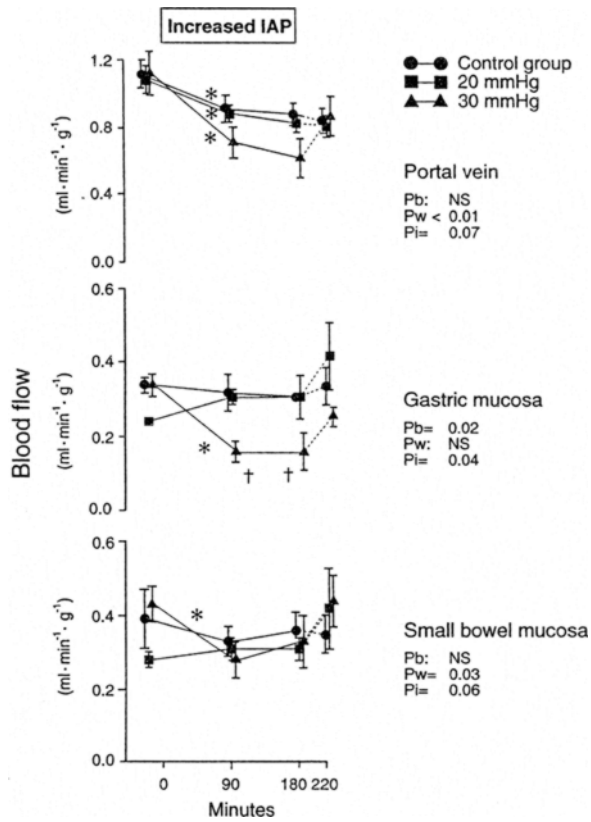

Fig. 1. Effects of increased intra-abdominal pressure (IAP) on blood flow in the portal vein, gastric mucosa, and small bowel mucosa of domestic pigs. Mean values ± standard error of mean (SEM). Three groups of seven animals each were used. *Significant reduction over time. †Significantly lower flow as compared with the other groups.

Table 2. Other gastrointestinal organ blood flow (ml/min/g) in three groups of domestic swine with different intra-abdominal pressures

Intra-abdominal pressure (IAP) (mm Hg)	Baseline	Increased IAP		End of experiment[a]	ANOVA (−10, 90, and 180 min)
		90 min	180 min		
Gastric muscularis					
0 (n = 7)	0.17 ± 0.04	0.13 ± 0.02	0.14 ± 0.03	0.12 ± 0.01	Pb: NS
20 (n = 7)	0.38 ± 0.19	0.26 ± 0.11	0.29 ± 0.12	0.29 ± 0.08	Pw: NS
30 (n = 7)	0.35 ± 0.11	0.27 ± 0.08	0.21 ± 0.09	0.33 ± 0.06	Pi: NS
Small bowel muscularis					
0 (n = 7)	2.17 ± 0.52	1.16 ± 0.35	0.74 ± 0.18	0.66 ± 0.13	Pb = 0.005
20 (n = 7)	1.31 ± 0.14	0.60 ± 0.17	0.56 ± 0.15	0.96 ± 0.49	Pw < 0.001
30 (n = 7)	0.93 ± 0.32	0.21 ± 0.04	0.15 ± 0.05	0.34 ± 0.09	Pi: NS
Colon whole wall					
0 (n = 7)	0.52 ± 0.07	0.43 ± 0.05	0.41 ± 0.08	0.43 ± 0.06	Pb: NS
20 (n = 7)	0.52 ± 0.05	0.50 ± 0.04	0.50 ± 0.06	0.59 ± 0.16	Pw = 0.013
30 (n = 7)	0.65 ± 0.04	0.51 ± 0.09	0.46 ± 0.09	0.56 ± 0.04	Pi: NS
Gall bladder					
0 (n = 7)	0.46 ± 0.09	0.47 ± 0.09	0.47 ± 0.08	0.44 ± 0.07	Pb: NS
20 (n = 7)	0.38 ± 0.07	0.38 ± 0.08	0.34 ± 0.06	0.56 ± 0.27	Pw: NS
30 (n = 7)	0.51 ± 0.10	0.34 ± 0.04	0.34 ± 0.10	0.63 ± 0.18	Pi: NS

[a] 40 min after normalization of IAP
Pb, Pw, and Pi are the probabilities by ANOVA for differences between groups, within groups, and of interaction, respectively
ANOVA, analysis of variance; NS, not significant

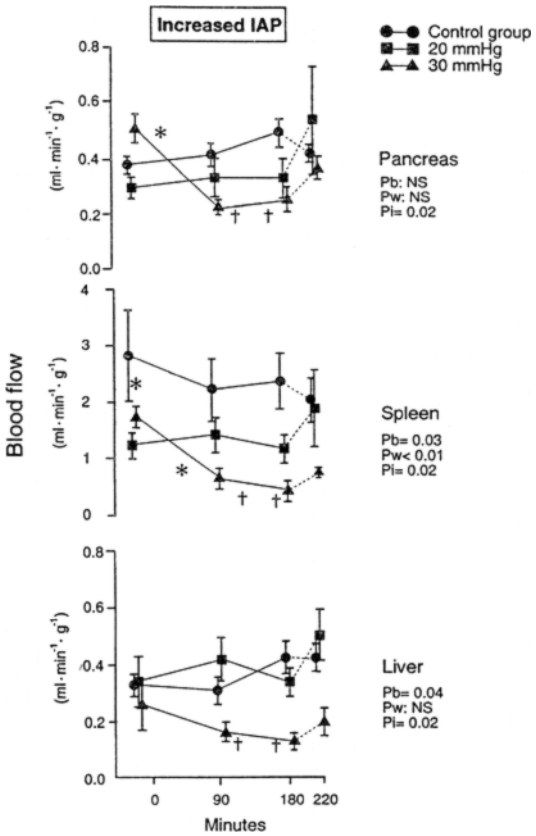

Fig. 2. Effects of increased intra-abdominal pressure (IAP) on blood flow in the pancreas, spleen, and liver of domestic pigs. Mean values ± standard error of mean (SEM). Three groups, of seven animals each were used. *Significant reduction over time. †Significantly lower flow as compared with the other groups.

0.001). The baseline blood flow did not differ significantly between the groups except in the spleen, where the control blood flow was significantly higher than in the other experimental groups (p = 0.05). As shown in Figs. 1 and Fig. 2 as well as Table 2, the blood flow in the group with an IAP of 30 mmHg, increased again 40 min after normalization of IAP in all gastrointestinal organs examined.

Vascular resistance

The systemic vascular resistance and the gastrointestinal vascular resistance remained stable over time in the control group and in the animals with an IAP of 20 mmHg, but increased markedly at an IAP of 30 mmHg (Table 3). The gastrointestinal vascular resistance in the animals with an IAP of 30 mmHg increased gradually over time, becoming significantly higher than the baseline value after 3 h of increased IAP (p < 0.01).

Serum lactate

As shown in Table 4, the concentration of serum lactate in femoral venous blood did not change significantly over time in the control animals and in the animals with an IAP of 20 mmHg. After 180 min at an IAP of 30 mmHg, the serum lactate concentration was significantly higher than the corresponding value at an IAP of 20 mmHg (p < 0.05).

Hematocrit

Hematocrit values did not change significantly within or between groups during the experiments, with the pooled value being 24.7 ± 0.4.

Table 3. Systemic vascular resistance and gastrointestinal vascular resistance in three groups of domestic swine with different intra-abdominal pressures

Intra-abdominal pressure (IAP) (mmHg)	Baseline	Increased IAP		End of experiment[a]	ANOVA (−10, 90, and 180 min)
		90 min	180 min		
Systemic vascular resistance (mmHg·min·kg·l^{-1})					
MAP-CVP/(CO/kg)					
0 (n = 7)	0.32 ± 0.02	0.39 ± 0.03	0.33 ± 0.02	0.38 ± 0.02	Pb: NS
20 (n = 7)	0.31 ± 0.01	0.33 ± 0.02	0.35 ± 0.03	0.32 ± 0.05	Pw = 0.048
30 (n = 7)	0.33 ± 0.02	0.42 ± 0.06	0.50 ± 0.11	0.24 ± 0.03	Pi: NS
Gastrointestinal resistance (mmHg·min·kg·l^{-1})					
MAP-PVP/(porta flow/kg)					
0 (n = 7)	1.37 ± 0.11	1.82 ± 0.16	1.82 ± 0.11	1.91 ± 0.16	Pb: NS
20 (n = 7)	1.46 ± 0.13	1.54 ± 0.17	1.72 ± 0.13	1.84 ± 0.16	Pw = 0.012
30 (n = 7)	1.76 ± 0.21	1.94 ± 0.25	2.67 ± 0.73[b]	1.85 ± 0.39	Pi: NS

[a] 40 min after normalization of IAP
[b] $p < 0.01$ as compared with baseline value
Pb, Pw, and Pi are the probabilities by ANOVA for differences between groups, within groups, and of interaction, respectively
MAP, mean arterial pressure; CVP, superior caval vein pressure; PVP, portal vein pressure; CO, cardiac output; ANOVA, analysis of variance; NS, not significant

Table 4. Serum lactate (mmol/l) in femoral venous blood in three groups of domestic swine with different intra-abdominal pressures

Intra-abdominal pressure (IAP) (mmHg)	Start of experiment	Increased IAP 180 min	End of experiment[a]	ANOVA (-10 min and 180 min)
0 (n = 7)	1.13 ± 0.06	1.11 ± 0.13	1.41 ± 0.22	Pb = 0.006
20 (n = 7)	0.76 ± 0.13	0.78 ± 0.23	0.74 ± 0.08	Pw: NS
30 (n = 7)	1.27 ± 0.22	2.54 ± 0.79[b]	2.06 ± 0.51	Pi: NS

[a] 40 min after normalization of IAP
[b] $p < 0.05$ as compared with control group after 180 min
Pb, Pw, and Pi are the probabilities by ANOVA for differences between groups, within groups, and of interaction respectively
ANOVA, analysis of variance; NS, not significant

IAP at 40 mmHg

In four animals the IAP was elevated to 40 mmHg and kept at this level for 3 h. At this IAP, the cardiac output and blood flow in various abdominal organs decreased markedly (Table 5). In the reperfusion phase, when the intra-abdomial pressure was reduced from 40 mmHg to normal, the animals became very unstable with profound hypotension, and two of the animals collapsed and died. An IAP of 40 mmHg for 3 h obviously was very harmful to the animals, so this part of the study was not completed.

Microscopic examination

An IAP of 20 or 30 mmHg was not found to be associated with mucosal damage in the corpus and antrum of the stomach or in the small intestine.

Discussion

It is well established that increased intra-abdominal pressure is associated with various changes in the central hemodynamics and gastrointestinal blood flow [1–3, 8, 11, 14, 17]. However, in most of the previous studies, the IAP was increased stepwise for short periods, whereas in the current study the IAP was maintained constant at high levels for a period of 3 h.

In this study the heart rate and arterial pressure did not change significantly when the IAP was increased to 20 or 30 mmHg. However, abundant Ringer's solution was administered to keep the arterial pressure close to normal. Our results are in agreement with previous observations [1, 11].

We found no significant changes in CO after elevation of the IAP to 20 or 30 mmHg. Similar observations were made by Diebel et al. [6]. On the other hand, other researchers have reported significant reductions in CO at an IAP of 20 to 25 mmHg [3, 17]. Kashtan et al. [14] showed that hypovolemic animals showed marked reduction in CO under increased IAP whereas hypervolemic animals had increased CO. Harman et al. [9] demonstrated that the reduction in CO observed under increased IAP could be normalized with intravenous fluids. Taken together, these results indicate that the effect of IAP on CO depends on the amount of fluid administered to the animal. It appears that the CO can be maintained at the normal level even in long-term experiments if a sufficient amount of fluid is administered. The superior caval vein pressure remained close to normal at an IAP of 20 mmHg, but increased significantly at an IAP of 30 mmHg. These findings are in accordance with earlier results obtained in short-term studies [2, 3, 16]. On the other hand Richardson and Trinkle [17] found reduction in central vein pressure with increased IAP. The increased venous pressure in the superior caval vein can be explained as result from reduced cardiac function caused by increased systemic vascular and gastrointestinal vascular resistance.

Table 5. Cardiac output and gastrointestinal organ blood flow in a group of domestic swine with an intra-abdominal pressure of 40 mmHg

	Baseline	Increased IAP		End of experiment[a]
		90 min	180 min	
Cardiac output (l/min)	4.15 ± 0.05	2.3 ± 0.46	1.89 ± 0.29	3.72 ± 0.15
Gastric mucosa (ml/min/g)	0.30 ± 0.07	0.15 ± 0.15	0.08 ± 0.04	0.40 ± 0.15
Small bowel mucosa (ml/min/g)	0.42 ± 0.06	0.11 ± 0.10	0.13 ± 0.07	0.38 ± 0.08
Colon (ml/min/g)	0.47 ± 0.04	0.28 ± 0.23	0.19 ± 0.09	0.59 ± 0.12
Liver (ml/min/g)	0.33 ± 0.06	0.05 ± 0.04	0.06 ± 0.04	0.32 ± 0.01
Pancreas (ml/min/g)	0.30 ± 0.02	0.14 ± 0.04	0.14 ± 0.04	0.44 ± 0.03

Note: $n = 4$, except for end of experiment, where $n = 2$
[a] 40 min after normalization of IAP

In the current study, the systemic vascular resistance was not found to be influenced by an increase in IAP to 20 mmHg. However, the resistance increased significantly when the IAP was maintained at 30 mmHg for 180 min. Increased systemic vascular resistance was observed earlier in short-term experiments [3, 4, 9, 14, 16]. The elevated systemic resistance probably is caused by the release of stress hormones.

Diebel et al. [6] found that the portal venous blood flow (PVBF) fell by 27% at an IAP of 10 mmHg and by 45% at an IAP of 30 mmHg, as compared with the baseline value. Rasmussen et al. [16] increased the IAP in pigs by carbon dioxide insufflation and observed significant reductions in PVBF at an IAP of 15 mmHg or higher. At 25 mmHg, the portal flow was 66% of the baseline value. In the current study, the PVBF decreased significantly at an IAP of 30 mmHg. However, the PVBF obtained at 20 mmHg did not differ from that of the control group, which appears to be in disagreement with the previously cited results. The discrepancy may be explained, at least partly, by the fact that the current results were obtained after long periods of increased IAP, and that a separate group of animals with normal IAP was used as controls. Nevertheless, there is general agreement that increased IAP is followed by reduced PVBF.

An increase in IAP was followed by a corresponding increase in portal vein pressure, whereas the arterial pressure remained fairly constant, even at 30 mmHg. This means that the arteriovenous pressure gradient in the portal circulation decreases substantially, which explains most of the fall in portal venous blood flow. However, considerable evidence has accumulated to show that increased intestinal venous pressure is associated with vasoconstriction and increased vascular resistance. Selkurt and Johnson [18] showed that the vascular resistance in the small intestine of dogs increased when the venous pressure was elevated from 0 to 30 cm of H_2O, and Johnson [13] provided evidence to show that it was the result of an active vasoconstriction. Fevang et al. [7] found increased local release of endothelin-1 and increased vascular resistance when the venous pressure was elevated to 50 mmHg in a closed loop of small bowel in pigs. The increased resistance in the portal circulation observed in the current study probably results from vasoconstriction caused by elevated pressure and the release of vasoactive factors in the portal circulation. Consequently, the fall in portal blood flow under increased IAP can be explained as resulting from reduced arteriovenous perfusion pressure and vasoconstriction.

Caldwell and Ricotta [3] investigated visceral blood flow in dogs with radioactively labeled microspheres. The IAP was elevated by inflating an intra-abdominal bag. They observed a marked fall in blood flow in most gastrointestinal organs after 30 min at an IAP of 20 mmHg. They also found a marked fall in CO, which did not, however, explain all the reduction in intestinal blood flow. Diebel et al. [6] found that hepatic artery blood flow and PVBF, as measured by Doppler flow probes, decreased markedly when the IAP was increased to 20 mmHg. Diebel et al. [5] also found that the intestinal mucosal blood flow in swine, as measured by laser Doppler flowmetry, decreased significantly at an IAP of 20 mmHg, despite the fact that the CO and arterial pressure remained constant.

In the current study, the CO and blood flow to various intestinal organs were not significantly changed even after 180 min at an IAP of 20 mmHg. No good explanation exists for the controversial results. However, different animal species, anesthesia, and technique of increasing the IAP may partly account for the discrepancy. An important factor may be the intravenous infusion of abundant fluid during the whole experiment.

In the current study, an IAP of 30 mmHg was followed by markedly reduced tissue blood flow in many intra-abdominal organs. This agrees with results obtained previously in short-term experiments [3, 5, 6]. A twofold increase in serum lactate in peripheral venous blood was found after 180 min at an IAP of 30 mmHg, indicating tissue ischemia. However, even an IAP of 30 mmHg was not followed by mucosal damage in the stomach and small bowel, which indicates that the tissue blood flow was not reduced to a level that causes tissue injury.

At IAP of 40 mmHg for 3 h, the CO and blood flow to intra-abdominal organs decreased markedly. In the reperfusion phase, profound hypotension was observed, and two of the animals died. Obviously, it is dangerous to maintain the IAP at this high level for longer periods.

Conclusion

An IAP of 20 mmHg did not cause significant changes in systemic or gastrointestinal blood flow, even when maintained at this level for 180 min, which can be relevant for clinical work such as laparoscopy. In animals with an IAP maintained at 30 mmHg for 3 h, the CO, heart rate, and arterial blood pressure remained fairly constant, whereas

portal venous blood flow and microcirculatory blood flow to various intra-abdominal organs decreased, although not to a level that caused tissue damage. The results from this study indicate that high IAP (>20 mmHg) over longer periods of time had serious consequences for the animals. This agrees well with clinical observations in patients with abdominal hypertension [12, 19]. An IAP kept at 40 mmHg for 3 h represented a serious trauma to the animals.

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