ANESTHESIOLOGY

Internal Carotid Artery Blood Flow Response to Anesthesia, Pneumoperitoneum, and Head-up Tilt during Laparoscopic Cholecystectomy

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EDITOR'S PERSPECTIVE

What We Already Know about This Topic

- Cardiac output is an independent regulator of cerebral blood flow in healthy awake humans
- The relationship between cardiac output and cerebral blood flow in anesthetized patients undergoing laparoscopy has not been previously characterized

What This Article Tells Us That Is New

- At steady-state depth of anesthesia, in patients undergoing laparoscopic cholecystectomy, creation of pneumoperitoneum decreased cardiac output and internal carotid artery blood flow while mean arterial pressure and end-tidal carbon dioxide levels remained unchanged

ABSTRACT

Background: Little is known about how implementation of pneumoperitoneum and head-up tilt position contributes to general anesthesia-induced decrease in cerebral blood flow in humans. We investigated this question in patients undergoing laparoscopic cholecystectomy, hypothesizing that cardiorespiratory changes during this procedure would reduce cerebral perfusion.

Methods: In a nonrandomized, observational study of 16 patients (American Society of Anesthesiologists physical status I or II) undergoing laparoscopic cholecystectomy, internal carotid artery blood velocity was measured by Doppler ultrasound at four time points: awake, after anesthesia induction, after induction of pneumoperitoneum, and after head-up tilt. Vessel diameter was obtained each time, and internal carotid artery blood flow, the main outcome variable, was calculated. The authors recorded pulse contour estimated mean arterial blood pressure (MAP), heart rate (HR), stroke volume (SV) index, cardiac index, end-tidal carbon dioxide (ET_{CO_2}), bispectral index, and ventilator settings. Results are medians (95% CI).

Results: Internal carotid artery blood flow decreased upon anesthesia induction from 350 ml/min (273 to 410) to 213 ml/min (175 to 249; –37%, $P < 0.001$), and tended to decrease further with pneumoperitoneum (178 ml/min [127 to 208], –15%, $P = 0.026$). Tilt induced no further change (171 ml/min [134 to 205]). ET_{CO_2} and bispectral index were unchanged after induction. MAP decreased with anesthesia, from 102 (91 to 108) to 72 (65 to 76) mmHg, and then remained unchanged (Pneumoperitoneum: 70 [63 to 75]; Tilt: 74 [66 to 78]). Cardiac index decreased with anesthesia and with pneumoperitoneum (overall from 3.2 [2.7 to 3.5] to 2.3 [1.9 to 2.5] $l \cdot min^{-1} \cdot m^{-2}$); tilt induced no further change (2.1 [1.8 to 2.3]). Multiple regression analysis attributed the fall in internal carotid artery blood flow to reduced cardiac index (both HR and SV index contributing) and MAP ($P < 0.001$). Vessel diameter also declined ($P < 0.01$).

Conclusions: During laparoscopic cholecystectomy, internal carotid artery blood flow declined with anesthesia and with pneumoperitoneum, in close association with reductions in cardiac index and MAP. Head-up tilt caused no further reduction. Cardiac output independently affects human cerebral blood flow.

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Cerebral blood flow is regulated by an interplay of neurovascular coupling, oxygen and carbon dioxide reactivity, sympathetic innervation, and autoregulation that buffers variations in mean arterial pressure (MAP).[1] Numerous cardiorespiratory changes induced by anesthesia and mechanical ventilation may therefore affect cerebral flow, and surgical techniques may compound the problems. Little is known about how implementation of pneumoperitoneum with carbon dioxide and head-up tilt positioning contributes to general anesthesia-induced decrease in cerebral blood flow in humans. Here, we investigated this question in patients undergoing laparoscopic cholecystectomy.

Although artificial pneumoperitoneum during laparoscopic cholecystectomy is usually well-tolerated, the method alters the patient's cardiovascular[2,3] and respiratory physiology,[4,5] challenging the control of cerebral blood flow. General anesthesia, mechanical ventilation, the reverse Trendelenburg position, and pneumoperitoneum may together lead to hemodynamic compromise. Insufflation of carbon dioxide increases systemic vascular resistance (SVR),[2] whereas increased intraperitoneal and intrathoracic pressures reduce venous return to the right heart, and hence stroke volume (SV) and cardiac output (CO). Pneumoperitoneum shifts the diaphragm cephalad,

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causing airway pressures to increase and functional residual capacity and lung compliance to decrease as a result of formation of basal atelectasis.[6] Positive end expiratory pressure (PEEP) used to preserve oxygenation and improve respiratory mechanics may further compromise venous return.[7] The head-up position improves respiratory mechanics but does not favor venous return to the heart. In the presence of hypovolemia and hypotension, hypocapnia may aggravate cerebral hypoperfusion,[8] the cerebrovasculature being highly reactive to the arterial partial pressure of carbon dioxide ($Paco_2$).[9–11]

No direct monitoring of cerebral blood flow is in routine clinical use, hence its optimization has customarily rested on indirect measures such as arterial blood pressure and arterial blood gases. Several studies have however found that also within the classic autoregulation plateau region (60 to 150 mmHg),[12] fluctuations in MAP are associated with fluctuations in cerebral arterial blood velocity.[13,14] Indeed, the autoregulation plateau seems to be narrow, sloped, less effective during hypotension than hypertension, and with poorer buffering for rapid than for slow MAP changes.[1,13,15] Many aspects of cerebral autoregulation, however, remain unresolved.

In healthy, awake humans, blood flow in the internal carotid artery was found to decline in association with reductions in CO, despite unchanged MAP.[16] Experimental studies using cerebral blood velocity[17–20] or xenon imaging[21] as index for cerebral perfusion support these findings. In surgical populations, the relationship between CO and cerebral blood flow is not well characterized.

We wanted to investigate whether cerebral blood flow would be affected by pneumoperitoneum, a routine surgical procedure that nevertheless presents a host of physiologic challenges. In patients undergoing elective laparoscopic cholecystectomy we assessed the effects of induction of anesthesia, positive pressure ventilation, pneumoperitoneum, and head-up tilt on internal carotid artery blood flow. These changes in blood flow were then related to continuous noninvasive MAP and CO measurements. We here demonstrate that internal carotid artery blood flow declines significantly in association with reduced CO, independently of depth of anesthesia, MAP, and end-tidal carbon dioxide ($ETco_2$). CO is an independent regulator of human cerebral blood flow.

Materials and Methods

Eligibility Criteria

We recruited healthy (American Society of Anesthesiologists [ASA] physical status I or II), nonobese (body mass index less than or equal to 32 kg/m^2) adults (at least 18 yr old) scheduled for day case laparoscopic cholecystectomy. All eligible patients in the study period (January 10 to March 10, 2018) were invited to participate. All patients gave written, informed consent to participate. Our procedures conformed to the Declaration of Helsinki, and the Regional Ethics Committee (Oslo, Norway; ref. No.: 2017/1064) and the Institutional Data Protection Officer (ref. No.: 2017/163) approved the study protocol and procedures.

Patients accepted as day cases are generally healthy, but quite a few take chronic medication (*e.g.*, idiopathic hypertension, hypothyroidism, or diabetes mellitus type II). To obtain a representative population such patients were included if they reported complying with their medication and if their arterial blood pressure and blood sugar measurements were within normal limits on the day of surgery. Patients with known cerebrovascular disease were not included. No formal statistical power calculation was conducted. A sample size at or above 15 patients was considered adequate based on our previous experience with measurements of internal carotid artery blood flow in healthy humans. The study was by design a nonrandomized, prospective, observational study.

Anesthesia Procedure

Our study was purely observational. All anesthetic and surgical procedures followed the unit's protocols and were performed by the unit's personnel. Patients were premedicated 30 to 60 min before operation with *per os* paracetamol 15 mg/kg, diclofenac 50 to 100 mg, dexamethasone 8 to 16 mg, and oxycodone depot formulation 5 to 10 mg. After 2 to 3 min preoxygenation with 100% oxygen, anesthesia was induced with remifentanil and propofol target controlled infusion based on patient age and ideal body weight. Appropriate conditions for endotracheal intubation were achieved with remifentanil; neuromuscular blockade was not used. Anesthesia was maintained with fentanyl 3 to 5 mcg/kg and infusions of remifentanil and propofol at the discretion of the anesthetist. Metoclopramide 10 mg and ondansetron 4 mg were given intravenously toward the end of surgery to prevent postoperative nausea and vomiting. Intermittent doses of ephedrine (10 mg) and phenylephrine (100 mcg) or a phenylephrine infusion were used when appropriate to uphold MAP.

Patients were ventilated by volume regulated pressure control ventilation with 40% oxygen in air, tidal volumes 5 to 6 ml/kg of ideal body weight, inspiratory to expiratory ratio 1:2 and PEEP 6 to 8 cm H_2O, targeting maximal airway pressures of 20 to 24 cm H_2O. Initial respiratory rate was 12 breaths per minute. Respiratory rate and tidal volume were adjusted as necessary to preserve eucapnia. Standard anesthesia monitoring included oscillometric arterial blood pressure (systolic, diastolic, mean) every five minutes, pulse oximetry, heart rate (HR), three-lead electrocardiogram, and capnography. A bispectral index was used to monitor depth of anesthesia. After carbon dioxide insufflation the intraperitoneal pressure was kept at 11 to 14 mmHg throughout the procedure. A few minutes after induction of pneumoperitoneum the patients were tilted head-up by 10 to 20 degrees.

Recordings

Mean internal carotid artery blood velocity was measured by Doppler ultrasound (8 MHz probe, insonation angle 60°, Mylab Alpha, Esaote, Adcare, Norway), approximately 2 cm above the bifurcation of the common carotid artery to avoid turbulent flow.[11] Noninvasive finger arterial pressure was recorded continuously from the middle left finger (Finometer finger pulse contour monitor, Finapres Medical Systems, The Netherlands) positioned at heart level, and MAP was calculated. The finger arterial blood pressure curve was calibrated and reconstructed against brachial arterial blood pressure using an upper arm cuff before the recordings.[22] SV and CO estimates were calculated beat to beat from the finger arterial blood pressure curve using the Modelflow algorithm.[22,23] Previous work has demonstrated good correspondence between SV calculated by this algorithm and SV measured by Doppler ultrasound during normovolemia and central hypovolemia, the algorithm being particularly accurate in following variations in stroke volume.[24,25] During cardiac surgery, CO estimated by this method corresponded well with pulmonary artery thermodilution CO measurements.[26]

Measurements of mean internal carotid artery blood velocity were recorded for 10 to 14 cardiac cycles, 4 to 6 times in each of the following states: (1) awake patient fully monitored at the operating table, (2) approximately two minutes after induction of anesthesia and endotracheal intubation, (3) approximately one minute after induction of pneumoperitoneum, with the patient in the horizontal position, and (4) approximately one minute after head-up tilt (*i.e.*, reverse Trendelenburg position). The median internal carotid artery velocity value (of the 4 to 6 means obtained at each state) was used in the subsequent analyses. The internal carotid artery diameter at the site of insonation was obtained in each state before recording velocity. Internal carotid artery beat volume was calculated from the median internal carotid artery velocity and vessel diameter. Internal carotid artery blood flow was calculated from internal carotid artery beat volume multiplied by the median HR in that state. HR, MAP, SV, CO, SVR, $ETCO_2$, peak airway pressure, PEEP, respiratory rate, and tidal volume were recorded concurrently with internal carotid artery velocity recordings (approximately 2-min recordings) by obtaining pictures of the anesthesia and pulse contour monitor screens every third second with the use of an iPad (Apple, USA). Median values were calculated for each state. Cardiac index, SV index, and SVR index were calculated, thus adjusting for the patients' body surface area. $ETCO_2$ in awake patients was sampled from the facemask during preoxygenation; during the other states $ETCO_2$ was sampled from the endotracheal tube.

Statistical Analysis

Reported values are medians with 95% CI calculated by the Hodges–Lehmann estimate, unless otherwise noted. The Friedman test for four related samples was used to test the difference across the four states. The Wilcoxon matched-pairs signed-rank test against a two-sided alternative was used to test differences between states for our primary outcome variable, internal carotid artery blood flow (StatXact, Cytel Studio 10, Cytel Inc., USA). For this test the level of significance was Bonferroni-corrected and set at $P < 0.01$. For ease of comparison with other work, the percentage changes in internal carotid artery blood flow, cardiac index, MAP, and HR between states were also calculated for each subject; medians and 95% CI of the percentage change were calculated. The internal carotid artery blood flow response to changes in cardiorespiratory variables attributable to anesthesia, pneumoperitoneum, and head-up tilt was modeled using linear mixed-effects multiple regression (Fit Model platform, Personality Standard least squares, Method REML, SAS-JMP 12 software for Windows, SAS Institute, USA). The aim of the multivariable analysis was to identify the cardiovascular or respiratory variable(s) that could predict a change in internal carotid artery blood flow, while controlling for confounders such as the use of vasopressors and for the correlation between observations from the same subject (repeated measures design). Internal carotid artery blood flow was the response variable. HR, SV index, cardiac index, MAP, and $ETCO_2$ were continuous predictors (fixed effects). The use of vasopressors at each time point (dichotomous variable: Yes/No) was entered as a categorical predictor (covariate, fixed effect). Subject identity was entered as a random effect to account for the correlation between repeated observations from the same subject. The restricted maximum likelihood method[27] was used for the estimation of fixed effects coefficients and variance component estimates for random effects. The covariance structure used was the Variance Component structure. A predetermined forward variable sequence was followed, initially entering MAP, then cardiac index and finally $ETCO_2$ and the use of vasopressors in the model. If cardiac index turned out to be a significant predictor, substitution with HR and SV index was attempted. Inspection of the residual plots revealed no deviations from the assumptions of normality and homoscedasticity. The statistical significance level was set at $P < 0.05$.

Results

Seventeen patients, four males and thirteen females, aged 45.5 yr (range 23 to 76), body mass index 28.4 (range 21.1 to 31.5), ASA physical status I or II were recruited. The patients' comorbidities included diabetes mellitus type II (2 of 17), hypercholesterolemia (2 of 17), idiopathic hypertension (6 of 17), bipolar disorder (1 of 17) and asthma (1 of 17). One female was excluded from analysis because of an unexpected observation of a possible internal carotid artery stenosis. In four of the remaining sixteen patients we were not allowed sufficient time to obtain measurements during pneumoperitoneum in the horizontal position;

these patients provided only partial data. All collected data were analyzed and no outliers were observed.

Propofol infusion rates [median (quartiles)] were 7.1 (5.9 to 7.9), 6.3 (5.8 to 7.6), and 6.1 (5.8 to 7.1) mg · kg^{-1} · h^{-1} after anesthesia induction, pneumoperitoneum, and head-up tilt, respectively. Corresponding remifentanil infusion rates were 0.28 (0.16 to 0.41), 0.30 (0.25 to 0.36), and 0.30 (0.24 to 0.39) mcg · kg^{-1} · min^{-1}. Ephedrine was given alone (8 of 16 patients) or in combination with phenylephrine (2 of 16 patients) to restore MAP after induction of anesthesia and head-up tilt. Median (quartiles) total doses of ephedrine (10 mg) or phenylephrine (0.1 mg) was 1 (0 to 2). Measurements of internal carotid artery blood velocity were done only after any administered vasopressors had taken effect and MAP was restored.

Table 1 presents absolute values of cerebrovascular, cardiovascular, and respiratory variables at each time point. Figure 1 summarizes group mean internal carotid artery flow and velocity, internal carotid artery diameter, cardiac index, SV index, HR, MAP, SVR index, and $ETCO_2$ in awake patients and after anesthesia, pneumoperitoneum, and tilt.

Effects of Anesthesia

Induction of anesthesia and tracheal intubation resulted in an 18% reduction in cardiac index (–28 to –9%; P = 0.001) and a 30% reduction in MAP (–37 to –24%; P < 0.001) compared with the awake state. The decline in cardiac index resulted from a fall in HR (P = 0.002); SV index remained unaltered, likely because of a marked decline in SVR index (fig. 1).

Internal carotid artery diameter declined (P < 0.010) on induction of anesthesia (table 1), whereas internal carotid artery beat volume was reduced by 27% (–38 to –20%; P < 0.001) and internal carotid artery blood flow was reduced by 37% (–45 to –31%; P < 0.001).

Effects of Pneumoperitoneum

Induction of pneumoperitoneum with the patient in the horizontal position induced a marked increase in SVR index (P < 0.001) and a fall in SV index (P < 0.005, fig. 1), causing cardiac index to decrease by a further 16% (–22 to –11%; P = 0.001). Compared with measurements after anesthesia induction, HR and MAP remained unaltered. Internal carotid artery beat volume decreased by an additional 16% (–22 to –14%; P = 0.026) upon insufflation of pneumoperitoneum, causing internal carotid artery blood flow to fall by an additional 15% (–29 to –7%; P = 0.026). The depth of anesthesia (bispectral index, infusion rates of propofol and remifentanil) did not change after induction of anesthesia, and $ETCO_2$ was kept unchanged by ventilator adjustments.

Effects of Head-up Tilt

Positioning the patient in the reverse Trendelenburg position did not induce further changes in internal carotid artery blood flow or internal carotid artery beat volume. Also, cardiac index remained unaltered, as SV index declined marginally (P = 0.024) but HR increased (+15%, P = 0.003) and regained preanesthetic values. SVR index, MAP, and $ETCO_2$ did not change (table 1).

Combined Effects of Anesthesia, Pneumoperitoneum, and Tilt

Overall, compared with the awake state, internal carotid artery blood flow declined by 48% (–55 to –43%, P < 0.001),

Table 1. Cerebrovascular, Cardiovascular, and Respiratory Variables at Four Different Time Points during Laparoscopic Cholecystectomy in 16 American Society of Anesthesiologists Physical Status I–II Patients

	Awake	After Induction of Anesthesia	After Pneumoperitoneum*	After Head-Up tilt
ICA blood flow, ml/min	350 (273–410)	213 (175–249)	178 (127–208)	171 (134–205)
ICA beat volume, ml	5.2 (4.0–5.7)	3.6 (2.9–3.9)	2.8 (2.0–3.3)	2.5 (2.0–3.1)
ICA diameter, mm	5.9 (5.2–6.2)	5.6 (5.1–5.9)	5.3 (4.8–5.6)	5.5 (5.0–5.7)
MAP, mmHg	102 (91–108)	72 (65–76)	70 (63–75)	74 (66–78)
Cardiac index, l · min^{-1} · m^{-2})	3.2 (2.7–3.5)	2.8 (2.3–3.1)	2.3 (1.9–2.5)	2.1 (1.8–2.3)
SV index, ml · m^{-2}	46.2 (37.7–51.1)	47.5 (39.3–50.7)	37.1 (29.4–41.0)	31.7 (27.1–37.2)
HR, beats/min	70 (63–75)	60 (55–65)	65 (65–70)	69 (63–73)
SVR index, dyn s · cm^{-5} · m^{-2}	2609 (2342–3208)	2051 (1732–2423)	2522 (2267–3102)	2770 (2294–3469)
P_{max}, cm H_2O		17 (16–17)	19 (18–19)	19 (18–19)
Tidal volume, ml		410 (375–435)	380 (355–405)	406 (370–430)
Respiratory rate, breaths/min		12 (12–13)	12 (12–13)	13 (12–14)
§$ETCO_2$, mmHg	32 (29–35)	38 (36–40)	38 (35–38)	38 (36–39)
Bispectral Index	94 (94–95)	33 (27–37)	35 (32–37)	32 (28–36)

*n = 12. §Sampled from humidifier filter on facemask when awake, else from endotracheal tube. Data are medians with 95% CI calculated by Hodges Lehmann's estimate.

$ETCO_2$, end-tidal carbon dioxide; ICA, internal carotid artery; Finger pulse contour estimated (Finometer) MAP, mean arterial pressure; HR, heart rate; SV, stroke volume; SVR, systemic vascular resistance; P_{max}, peak airway pressure.

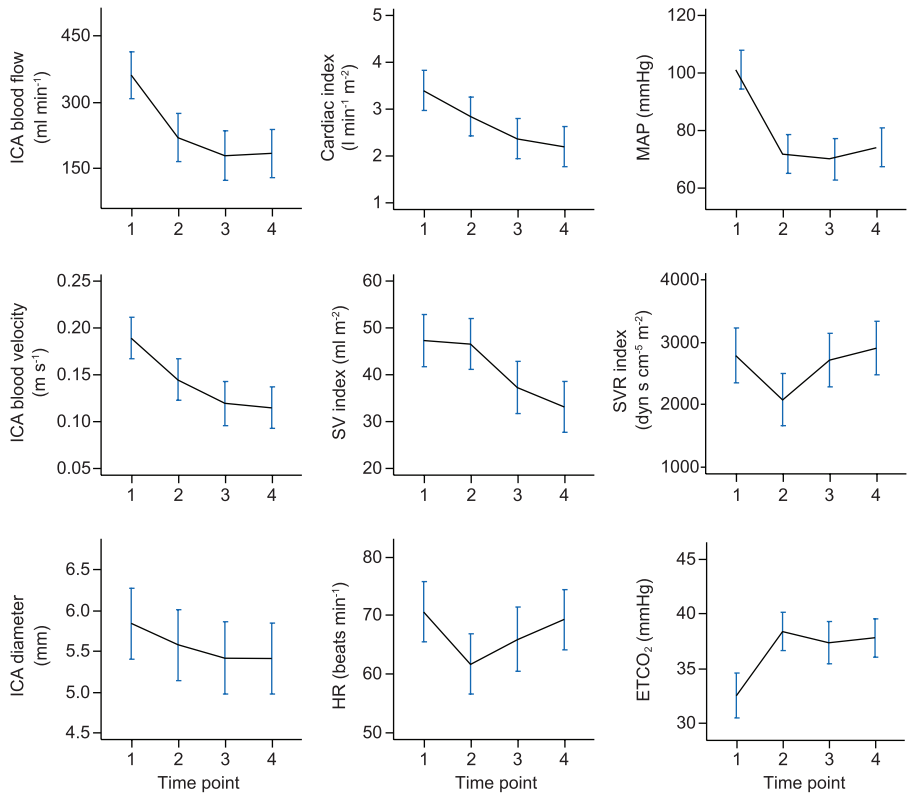

Fig. 1. Cerebrovascular and cardiovascular changes during laparoscopic cholecystectomy in 16 healthy day-surgery patients in propofol–remifentanil anesthesia. Values were measured at four time points: (1) awake, (2) after anesthesia induction and intubation, (3) after pneumoperitoneum, and (4) after head-up tilt. ICA, internal carotid artery; noninvasive finger pulse contour estimated MAP, mean arterial pressure; SV index, stroke volume normalized to body surface area; HR, heart rate; SVR index, systemic vascular resistance normalized to body surface area; $ETCO_2$, End-tidal carbon dioxide sampled from facemask (awake state) or endotracheal tube. Data are means with 95% confidence bars.

internal carotid artery beat volume by 47% (–54 to –42%, $P < 0.001$), and cardiac index by 36% (–41 to –32%, $P < 0.001$; fig. 1). The Friedman test confirmed that internal carotid artery blood flow was significantly different among the states ($P < 0.001$).

Mixed-effects Model

A linear mixed-effects model explained 88% of the variance in internal carotid artery blood flow (Adjusted $R^2 = 0.88$; $P = 0.001$). Cardiac index and MAP contributed significantly to internal carotid artery blood flow variance (fig. 2). $ETCO_2$ and the use of vasopressors did not contribute and were therefore removed from the model. A drop of 1 l · min^{-1} · m^{-2} in cardiac index predicted a drop of 88 ml/min in internal carotid artery blood flow ($P < 0.001$), whereas a drop of 10 mmHg in MAP predicted a drop of 26 ml/min in internal carotid artery blood flow ($P < 0.001$). Of the total random variance, 75% was attributed to variability between subjects. When SV index and HR were introduced as predictors instead of cardiac index, a reduction of 10 ml · m^{-2} in SV index predicted a 64 ml/min reduction in internal carotid artery blood flow ($P < 0.001$), a reduction of 10 beats/min in HR predicted a reduction of 63 ml/min in internal carotid artery blood flow ($P < 0.001$), and a reduction of 10 mmHg in MAP predicted a reduction of 21 ml/min in internal carotid artery blood flow ($P < 0.001$).

Discussion

We here demonstrate that in ASA physical status I–II patients undergoing elective laparoscopic surgery, internal carotid artery blood flow declined by 48% from the awake state to the setting with anesthesia, pneumoperitoneum, and head-up tilt. Although reduced cerebral metabolism attributable to anesthesia likely contributed, we found that cardiac index and MAP were major predictors of the internal carotid artery blood flow response. These findings contrast the classical cerebral autoregulation view and introduce cardiac output as an independent effector of cerebral blood flow during laparoscopic surgery.

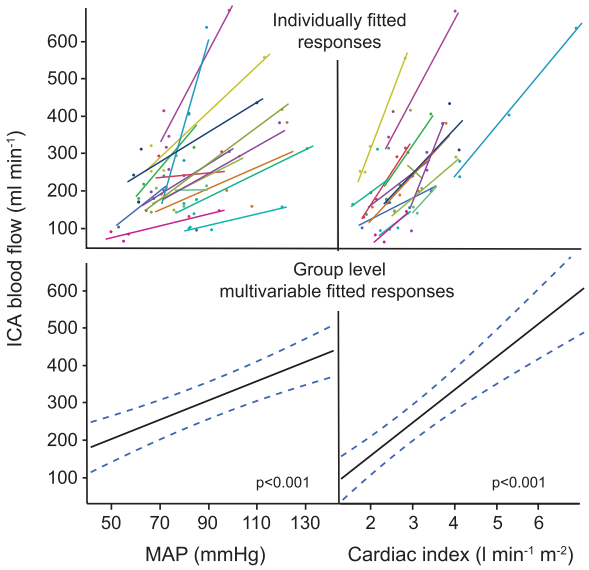

Fig. 2. Concomitant effects of cardiac index and blood pressure on internal carotid artery (ICA) blood flow. *Upper panels*: Individual lines of fit for each of 16 patients. *Lower panels*: Predicted ICA blood flow response to changes in cardiac index and mean arterial blood pressure (MAP) by mixed-model multiple regression. Measurements taken at four time points in 16 patients undergoing day-surgery laparoscopic cholecystectomy.

Induction of pneumoperitoneum decreased cardiac index (–16%) and internal carotid artery blood flow (–15%) despite unaltered MAP, $ETCO_2$, bispectral index readings, and infusion rates of anesthetic agents. The observed effect of cardiac index on human cerebral blood flow during general anesthesia is in line with our findings in awake healthy volunteers,[16] who experienced a 15% reduction in internal carotid artery blood flow during a 30% acute cardiac index reduction, despite preserved MAP. These results may have important implications for treatment strategies.

Several previous studies have reported on the relation between cerebral perfusion and acute changes in CO in awake healthy volunteers,[16–19,28] as reviewed.[20] However, most of these studies measured cerebral blood velocities rather than flow. The novelty of the present study lies in assessing internal carotid artery diameter as well as internal carotid artery blood velocity at each study condition, thus preventing changes in internal carotid artery diameter[1,29,30] from affecting the results. This method enabled us to estimate the effect of a drop in cardiac index and MAP on cerebral blood flow during general anesthesia in a surgical population.

Several factors interacted to decrease cardiac index, and thus cerebral flow, during laparoscopic cholecystectomy (fig. 1). Induction of anesthesia and mechanical ventilation reduced cardiac index (–18%) by reducing HR, whereas SV index was maintained by longer filling times and reduced SVR index. Reduced venous return attributable to positive-pressure ventilation likely contributed to reduce cardiac index.[31] Pneumoperitoneum decreased cardiac index further (–16%) through a marked drop in SV index, although HR returned to preanesthetic levels. Sympathetic stimulation and release of hormones such as renin–aldosterone, vasopressin, and catecholamines induced by insufflation of the peritoneum[2,32] probably caused the 21% SVR increase, which maintained MAP despite the decrease in cardiac index.

Increases in SVR as large as 60%, and 30% to 40% increases in MAP, have been reported upon induction of pneumoperitoneum during nitrous oxide and isoflurane anesthesia.[3] Reported effects of pneumoperitoneum on cardiac index vary, however, likely as a result of differing anesthetic protocols. Cardiac index measured by transesophageal echo-Doppler assessment did not change upon pneumoperitoneum during sevoflurane anesthesia despite large increases in SVR and MAP,[33] whereas other studies found 15% to 20% reductions in cardiac index upon pneumoperitoneum during intravenous[34] or inhalation anesthesia.[3] Cerebral blood flow may thus be variably affected by pneumoperitoneum.

Our noninvasive study design did not allow us to distinguish the effect of reduced cardiac index on internal carotid artery blood flow from possible effects of increased cerebral vascular resistance. Vasopressin induces powerful vasoconstriction in isolated human cerebral arteries.[35] Cerebral vasoconstriction mediated by hormone release and by direct sympathetic activation on the cerebral circulation might have contributed to the fall in internal carotid artery blood flow during pneumoperitoneum.

Targeting a MAP greater than 65 mmHg and preserving eucapnia is a commonly used strategy to preserve cerebral blood flow in a clinical setting, based on the concept of a MAP plateau where autoregulation is supposed to maintain flow. Lassen's classical curve was, however, composed from mean values of 11 subject groups in 7 studies,[12] and a more pressure-passive relationship between cerebral blood flow and MAP has been indicated.[1,36] Rapid fluctuations in MAP of 10 to 20 mmHg were associated with fluctuations in cerebral arterial blood velocity,[13,14] and cerebral autoregulation seems to buffer hypotension less effectively than hypertensive challenges.[1] Though cerebral autoregulation was thought to remain intact during propofol–remifentanil anesthesia,[37–42] these studies extrapolated cerebral blood flow from velocity recordings and did not control for concomitant cardiovascular changes. In the present study, the initial fall in MAP probably effected the marked drop in internal carotid artery blood flow upon induction of anesthesia, though neurovascular coupling and reduced cardiac index contributed. MAP was subsequently kept stable with a fluid bolus and intermittent doses of vasopressors if needed. The continuing decline in internal carotid artery

blood flow during surgery thus was unlikely to be due to reduced MAP.

Reduced cerebral blood flow during propofol anesthesia has been attributed to reductions in cerebral metabolism[43,44] (*i.e.*, neurovascular coupling[1]). In anesthetized healthy volunteers examined with positron emission tomography, target concentrations of propofol up to 2.5 mcg/ml resulted in a 54% reduction in cerebral glucose metabolic rate and a 47% reduction in total cerebral blood flow.[43] That study reported unchanged MAP and $Paco_2$ during propofol anesthesia, but HR declined and CO was not measured. In the present study, reduced cerebral metabolism probably was an important contributor to the large reduction in internal carotid artery blood flow (–37%) after induction of anesthesia, though this effect could not be separated from concurrent effects of reduced MAP and cardiac index. Throughout surgery, bispectral index was unchanged; thus other mechanisms than reduced cerebral metabolism must have acted to further reduce internal carotid artery blood flow.

Carbon dioxide is a powerful regulator of cerebral blood flow. Laparoscopic surgery is associated with reductions in total lung volume, functional residual capacity, and lung compliance,[5,45] and peritoneal insufflation with carbon dioxide increases $Paco_2$. Increased minute ventilation is needed to prevent hypercapnia and avoid impaired cerebral autoregulation.[1] In the present study, $ETco_2$ was kept stable after induction of anesthesia by altering ventilator settings; consequently, $ETco_2$ did not statistically affect cerebral blood flow.

The reverse Trendelenburg position did not further decrease cardiac index or internal carotid artery blood flow compared with the horizontal position. Both surgical stimulation and ephedrine used to preserve MAP likely contributed to increase cardiac contractility and heart rate, and thus to uphold cardiac index during tilt. The surgical protocol in the present study (*i.e.*, inducing pneumoperitoneum with the patient in the horizontal position) might have contributed to hemodynamic stability by preventing large reductions in venous return.[46] A previous study in which pneumoperitoneum was induced after 10 min in the reverse Trendelenburg position reported a 50% decline in cardiac index.[3]

The present study was performed in day-surgery patients without known cardiovascular or cerebrovascular pathology apart from controlled idiopathic hypertension. Our findings were uniform, substantial, and statistically significant even in a small study sample. The large total reduction observed in internal carotid artery blood flow (48%) had no apparent clinical consequences for our patients, but similar changes could predispose fragile patients to cerebral ischemia during laparoscopic procedures. Marked cardiovascular changes during laparoscopic cholecystectomy, though no immediate adverse events, were observed in patients with severe cardiovascular disease (ASA physical status III–IV).[47] Studies of ASA physical status I–II patients showed smaller effects.[33,48] A multifaceted approach to managing cerebral flow during surgery is warranted.[20] Optimizing CO in addition to preserving MAP, tailoring doses of intravenous anesthetic agents, and maintaining eucapnia may alleviate reduced cerebral perfusion in patients prone to hemodynamic decompensation.

Strengths and Limitations

A strength of our study is that internal carotid artery blood flow was measured, whereas previous studies reported only cerebral blood velocities and assumed arterial diameter to be constant. We found the decrease in internal carotid artery blood flow to be partly attributable to decreased internal carotid artery velocity and partly to a decrease in internal carotid artery diameter (table 1). Reduced vessel diameter may have resulted from reduced MAP after induction of anesthesia; experimental lowering of MAP by 20% using lower body negative pressure has been shown to induce a 5% decline in internal carotid artery diameter.[30] Internal carotid artery should not be considered a rigid vessel in studies of cerebral perfusion.

$ETco_2$ monitoring may underestimate $Paco_2$ during laparoscopic surgery as a result of an increase in alveolar-arterial partial pressure difference of carbon dioxide. The marked reduction in cardiac index in the present study may have contributed to $Paco_2$ underestimation as a result of reduced lung perfusion. $ETco_2$ in the awake state could not be compared with values during anesthesia, pneumoperitoneum, and tilt, as the former was sampled from the humidifier filter connected to a facemask with high-flow oxygen whereas the latter were sampled from the filter connected to the endotracheal tube. As we could not quantify the reduction in cerebral metabolism, the contribution of cardiac index and MAP to internal carotid artery blood flow changes upon induction of anesthesia may be overestimated in the regression analysis.

Conclusion

In day-surgery patients undergoing laparoscopic cholecystectomy under total intravenous anesthesia, internal carotid artery blood flow declined markedly after anesthesia, positive pressure ventilation, and pneumoperitoneum. Notably, reduced internal carotid artery blood flow was independently associated with reduced cardiac output, despite unchanged MAP, depth of anesthesia, and $ETco_2$. Our findings imply that noninvasive cardiac output monitoring could be of use in the operating theatre, to better individualize treatment of perioperative cardiovascular perturbations. Laparoscopic surgery is considered minimally invasive, but studies of its effects on cardiac output, cerebral perfusion, and long-term patient-reported outcomes are warranted, especially in fragile patients predisposed to adverse cerebrovascular events.

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Competing Interests

The authors declare no competing interests.

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