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ADVANCES IN ANESTHESIA

Anesthetic Considerations for Robotic Surgery in the Steep Trendelenburg Position

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Keywords
• Robotic surgery • Trendelenburg • Prostatectomy • Anesthesiology

Key Points

- Because of the excellent results, it can be predicted that an increasing number of patients will undergo robot-assisted procedures with CO_2 pneumoperitoneum (PP) and steep Trendelenburg position. Fortunately, the human body has a remarkable yet incompletely understood capacity to withstand the effects of a CO_2 PP and steep Trendelenburg position during general anesthesia.
- Although individual responses vary and should be monitored, effects on most organs are modest and should not be an obstacle to providing optimal surgical exposure during robot-assisted prostatectomy, cystectomy, or hysterectomy. Pre-existing intracranial pathology (mass lesions and edema) needs to be excluded because it is currently the most significant absolute contraindication.
- Painstaking attention to positioning is of overriding importance. Continual awareness of the primary importance of coronary and cerebral perfusion pressures (CPPs), rather than the more common attention to mean arterial pressure (MAP), is fundamental to safeguard cardiac and cerebral perfusion.
- The interpretation of MAP needs to take the effects of height differences and site of pressure measurement into account. Further experience and study will refine the perioperative management, in particular with regard to ventilation strategies, fluid management, and postoperative analgesia.

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INTRODUCTION

An increasing number of surgical procedures are becoming robot assisted to optimize surgical precision, minimize incisional trauma and postoperative scarring, hasten postoperative recovery, and minimize postoperative pain. During robot-assisted surgery on the uterus, bladder, or prostate, optimal surgical exposure requires the application of a CO_2 PP with a very steep Trendelenburg position (approximately 40°). The challenges that these conditions present to anesthesiologists are reviewed.

The largest procedural and perioperative experience exists with prostatectomy, and this procedure is the focus of this review, but the concepts apply to other procedures as well. The purpose of this review is to share as much practical information as possible developed during the authors' experience in the care of more than 2000 patients [1], to review the effects of combined CO_2 PP and steep Trendelenburg position on different organs systems, to examine how this might affect choice of agents and techniques, and to identify areas that require further study.

PREOPERATIVE CONSIDERATION

Although no specific guidelines apply to the preoperative care of these patients, it may be important to rule out intracranial pathology, carotid or basilar artery disease, or glaucoma (vide infra). Particular attention to the cardiovascular and pulmonary systems review and to comorbidities of these organ systems is warranted due to the implications of laparoscopy and steep Trendelenberg positioning. Obesity may complicate further the positioning considerations (discussed later).

POSITIONING

To avoid having to repeat positioning several times, it is useful to standardize this process as much as possible. Positioning is vital to both the safety of anesthetic care and to the conduct of surgery and thus justifies the additional time and effort it often requires. Although variations in technique or equipment exist between institutions, the concepts that are presented should be widely applicable.

To prevent patients from sliding cephalad, shoulder braces are used in the authors' practice. Concern for injury to the brachial plexus has led many practices to avoid use of shoulder braces. Although a nonsliding mattress has been recommended instead of shoulder braces, this does not suffice, in the authors' experience, to prevent patients from sliding with this degree of Trendelenburg positioning [2]. The shoulders are shielded from shoulder braces with a semisoft, thick custom-made headrest (Figs. 1 and 2). The head rests against that part of the pillow that gives away slightly between both braces in an attempt to evenly distribute the body weight across the shoulders, the part of he neck that makes contact with the head rest (the spinous processes of C7 and T1), and the head of the patient (Fig. 3). Excessive pressure on the head may strain the cervical spine, whereas excessive caudad pressure on the shoulders can injure the brachial plexus [3]. The brace holders have to be placed sufficiently medial to prevent

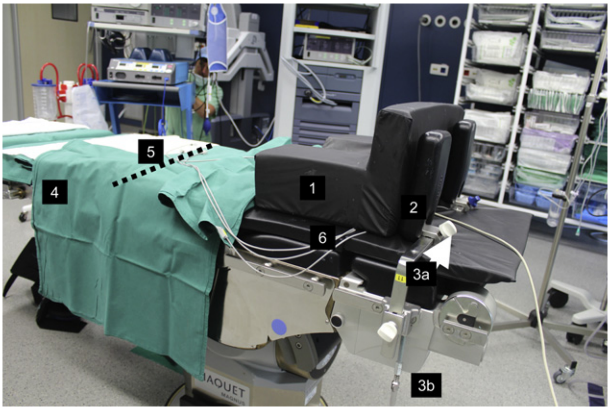

Fig. 1. Initial preparation. [1] The head is supported by a thick, soft headrest made of material that does not slide on the underlying mattress. [2] The pillow protects the shoulders from direct contact with the shoulder braces. [3a] The braces are placed sufficiently medial to prevent the head from sliding in between the two braces (also see Fig. 4); [3b] Extralong screws facilitate fixation to the side rails of the operating table. [4] The draw sheet is placed low enough so it can hold the entire hand. [5] The perineum has to align perfectly with the end of the operating table. [6] ECG cables should be placed underneath the pillow to avoid them from making skin contact because Trendelenburg increases the pressure.

the patient from sliding in-between the braces. To facilitate fixation of the braces to the side rails of the table, the authors have found extralong screws useful.

The draw sheet underneath the patient is placed low enough (before positioning the patient on the table) to ensure the arms and hands can be tucked within the sheath. To avoid direct contact or pressure of arms and hands against the leg holders, additional padding may be needed. Careful elbow padding is essential, with the thumbs in the anatomically neutral position (thumbs to the ceiling) while avoiding constrictive pressure on the arms from the drapes. When the arms are secured to the body with drapes, sliding of the patient after head-down positioning may cause a tourniquet effect, which can cause severe rhabdomyolysis and compartment syndrome, especially during lengthy procedures in obese patients [4]. Extensions have to be available for patients whose arms do not fit comfortably on the table, and the fact that there is not access to the arms during the procedure must be considered during the anesthetic planning.

INITIAL POSITIONING

First and foremost, the perineum must align with the end of the operating table that remains after removal of the bottom portion when the legs are placed in the leg holders. If a patient is too cephalad, the robot is not able to wheel-in sufficiently close to the surgical field between the patient's legs, especially if the patient slides up a few more centimeters on assuming the Trendelenburg position

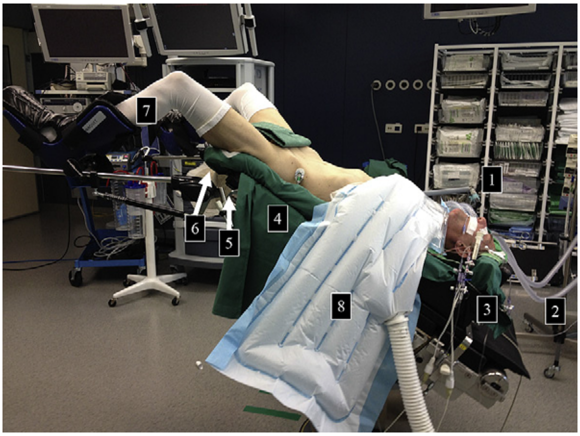

Fig. 2. The patient installed. [1] The bar of the ether screen is positioned only a few centimeters above the face to shield the face from robotic arms; a towel still needs to be placed on the face. Note absence of nasogastric tube. [2] Condensed water in the tubing could flow into the endotracheal tube if the head would be positioned lower. [3] Because the transducer is placed at the ear canal, the displayed arterial pressure will overestimate the arterial pressure at the level of the heart. [4] The circumferential pressure by the drapes around the arms should not be excessive. [5] The perineum has to perfectly align with the end of the table. [6] The draw sheet has been positioned sufficiently low so it can contain and protect the hands. [7] Both the choice of leg-holders and positioning itself are important to avoid lower leg compartment syndrome. [8] Forced warm air heating.

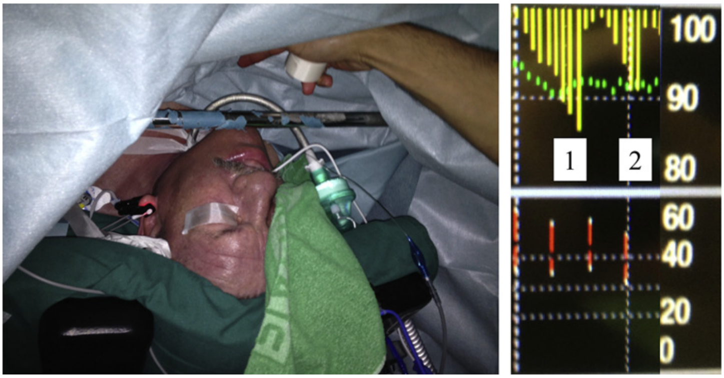

Fig. 3. Endobronchial intubation on assuming head-down tilt. Patient with the trachea intubated with an armored endotracheal tube via a preexisting tracheostomy. Little place is available to manage the airway after placing the patient in head-down tilt due to the bar of the ether screen that helps protect the face against excursions of the robotic arm. Initial endobronchial intubation [1] was recognized and the tube pulled back but reoccurred after placing the patient in Trendelenburg position [2].

(see Fig. 2). If a patient is too caudad, the pelvis may rotate, causing strain on the lumbar spine.

The choice of leg holders and positioning of the legs are important. During the bulk of the procedure, the legs have the lowest perfusion pressure because they are at the highest point relative to the heart. The authors have observed a single patient who suffered a bilateral calf compartment syndrome requiring bilateral fasciotomies, which was believed caused by a poor choice of leg holders, possibly combined with poor positioning of the legs. Enhanced attention to properly fitting and padded leg holders has been associated with no similar events since then.

ECG cables should not be positioned between the pillow and the patient's shoulders or head to avoid skin injury, and ECG pads should be applied where no direct pressure is expected.

POSTINDUCTION

No clear recommendation can be made with regard to placing a nasogastric or orogastric tube. Although some investigators argue it may prevent leakage from oral and gastric contents into the eyes during the head-down position, other investigators argue it may promote spillage by rendering the sphincters insufficient. The risk of aspiration is believed low because (1) the increased intra-abdominal pressure causes changes of the lower esophageal sphincter that allow maintenance of the pressure gradient across the gastroesophageal junction [5] and (2) the head-down position should help prevent any regurgitated fluid from entering the lower airway [6].

The Trendelenburg position and gravity cause any saliva to drip down onto the face of the patient and the towels. Because this occasionally can be pronounced, one of the authors (JFAH) prophylactically administers atropine or glycopyrrolate.

The horizontal bar of the ether screen is applied 2 cm to 3 cm above the patient's nose in an effort to allow the robotic arms to move as freely as possible (see Fig. 2). This minimum distance between the tip of the nose and the bar needs to be respected to avoid injury to the face (see Fig. 3), even after securely locking the bar into the holder on the side rails of the table. Additional padding should be applied between the nose and the bar, covering the patient's entire face. The bar and padding serves to protect the face from the robotic arms' movements and instruments that may be used above the face of the patient. The face is invisible and difficult to recognize or discern from other structures by the surgical team once the sterile drapes have covered the entire patient.

Securing the endotracheal tube is especially important, because the horizontal bar impedes further access to the airway, and the weight of breathing circuit hoses must be supported in a manner such that they do not promote the patient becoming inadvertently extubated (personal experience [JFAH]) at the beginning of the OLV Robotic Surgery Institute [1] program). After institution of the steep Trendelenburg position, cephalad migration of the carina relative to the vocal cords causes a shortening of the trachea of 0.4 ± 0.2

cm, which may result in unintentional endobronchial intubation. This may initially remain unnoticed because an increase in ventilatory pressures is anticipated, and thus confirmation of the tracheal tube positioning is recommended after patient repositioning [7,8]. In one of the authors' patients with a tracheostomy, initial endobrochial intubation of the armored tube in the supine position was recognized, the endotracheal tube was pulled back, and saturation improved, only to worsen on assuming the Trendelenburg position. It was initially suspected the CO_2 PP and Trendelenburg position were causing the desaturation, but fiberoptic bronchoscopy confirmed the tube had again migrated endobronchially (Fig. 4). Because positioning alone does not affect oxygenation in most patients (discussed later), endobronchial intubation should be suspected when desaturation occurs on assuming the Trendelenburg position.

All cables and connections (ECG cables, blood pressure cuff tubing, and so forth) need to be long enough and provide enough slack to prevent traction or impingement when a patient is placed head-down. To ensure easy intravenous access after the patient is positioned head down, an additional extension to the intravenous line can be useful. Drapes should be secured low enough relative to the surgical field so no traction is exerted after placing the patient head down. A forced air-warming blanket is applied to the upper body as a routine, but the Trendelenburg position does not require special perioperative thermal precautions or management [9].

Just before positioning the robotic arms in-between a patient's legs, the patient is brought in the full steep Trendelenburg position. This may often require the legs to be extended at the hips, with particular care taken not to overstretch the

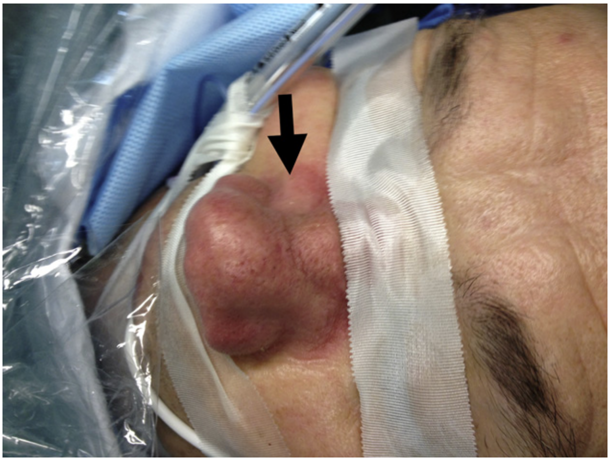

Fig. 4. Nasal injury. The bar of the ether screen has impinged (*arrow*) on the bridge of the nose. The ether screen needs to be securely fixed and the face needs to be protected. Intermittent direct inspection may be useful.

hips. It is important to remember the legs are down when the supine position is resumed much later, because this may worsen the hypotension often seen on resuming the supine position from decreased preload.

After the instruments of the robotic arms have been placed inside the patient's abdomen, the remote control of the table should be secured so it cannot inadvertently be manipulated–the consequences might be dire.

Provisions for effective communication should be established, because the noise from cooling the bulky equipment as well as the distance between the surgical field and surgeon's console makes communication difficult at times. The authors' robot has been equipped with microphones and loudspeakers.

Blood collection devices used to estimate blood loss should be placed well in sight of the anesthesiologist. Although seemingly stating the obvious, the equipment is bulky, and the room tends to become crowded.

EFFECTS ON ORGAN SYSTEMS

Hemodynamics

Hemodynamic changes during the different stages of the procedure with a 45° head-down tilt and an intra-abdominal pressure of 11 mm Hg to 12 mm Hg are presented in Fig. 5 [10]. There was no effect on cardiac performance, and filling

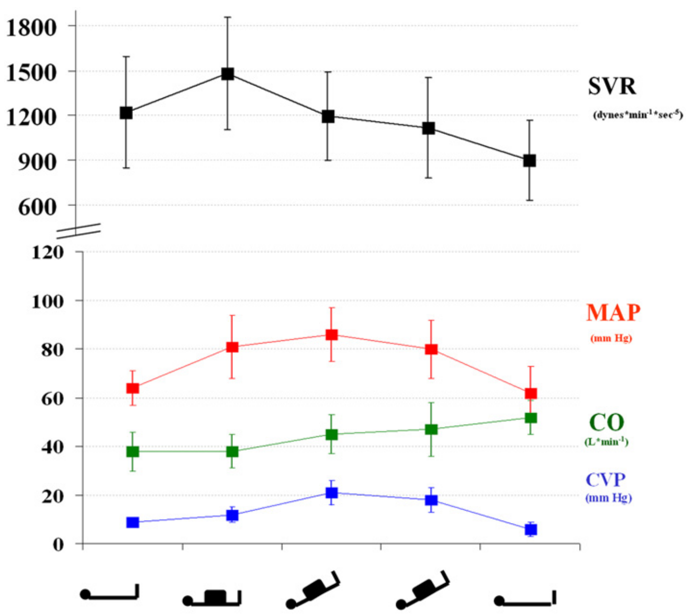

Fig. 5. Hemodynamic changes throughout the procedure. Different stages are presented in the X axis (symbols are self-explanatory). CO, cardiac output. (*Data from* Lestar M, Gunnarsson L, Lagerstrand L, et al. Hemodynamic perturbations during robot-assisted laparoscopic radical prostatectomy in 45° Trendelenburg position. Anesth Analg 2011;113(5):1069–75.)

pressures that had increased 2-fold to 3-fold normalized immediately after surgery.

Parameters of cardiac function as assessed by transesophageal echocardiography remained unchanged. Because cardiac output remains preserved during the procedure, alterations in MAP are caused by reciprocal changes in systemic vascular resistance (SVR). These blood pressure changes are most pronounced after applying the CO_2 PP (increased SVR, presumably due to direct mechanical compression of the abdominal arterial vasculature as well as neurohumoral factors [11–13]) and on resuming the supine position (decreased SVR with increased cardiac output). The latter may occasionally be pronounced; hypotension at that time can be attenuated or treated by slowly resuming the supine position, by ensuring the legs are not in the downward position, or by administering a judicious amount of phenylephrine. A constant mixed venous O_2 concentration indicates O_2 supply/demand of the body remains well preserved.

The rise in central venous pressure (CVP) immediately after assuming the steep Trendelenburg can occasionally be pronounced (>40 cm H_2O) but gradually lessens. These high filling pressures reflect the increased intrathoracic pressure from the weight of the abdominal contents on the diaphragm, rather than being indicative of hemodynamic deterioration. The intracavitary filling pressures do rise, but the transmural pressures in the right atrium and right ventricle seem largely unaffected because the right atrium and right ventricle do not enlarge on echocardiographic examination [10]. Consequently, the (very) high CVP as such does not imply a need to avoid fluids–to the contrary, a high CVP may actually mask hypovolemia [14,15]. Monitoring for trends over time is, therefore, particularly important, combined with careful monitoring of blood loss. Venous return seems well preserved during the combined CO_2 PP and Trendelenburg position because early filling flow velocity across the mitral valve is increased by 25% [10].

Nondependent areas of the body may be most at risk of hypoperfusion. When considering the coronary perfusion pressure, it is important to consider the position of the pressure transducers used for MAP and CVP measurements. When placing a patient in the steep Trendelenburg position, the vertical position of the external ear canal relative to the middle of the right atrium increases by approximately 20 cm. If the transducer is positioned at the ear canal, the MAP (and CVP as well) is overestimated by 20 cm H_2O or 14.7 mm Hg. CPP, however, does not change because MAP and CVP increase by an equivalent amount. Therefore, placing the transducers at the ear canal allows easy calculation of the CPP, but risks displaying deceivingly satisfying MAP values for the heart and nondependent body parts.

Gas exchange

Although the individual effects of a CO_2 PP and moderate degrees of head-up or head-down tilt separately on pulmonary gas exchange have been well described [6,16], until recently few data existed on their combined effects on lung function.

Induction of anesthesia decreases the functional residual capacity and thus the alveolocapillary membrane surface across which gas exchanges occur. Even though a CO_2 PP and steep Trendelenburg position are expected to worsen atelectasis and further reduce the functional residual capacity of the lung, a study the authors performed showed that venous admixture did not change, and changes in dead space ventilation were modest (which was also indicated by the absence partial pressure of end-expired CO_2 [P_ECO_2]/Pa_{CO_2} changes) (Fig. 6) [17].

The approximately 50% dead-space ventilation (including apparatus dead space) throughout the procedure is almost identical to the 51% reported during general anesthesia [18]. The 10% venous admixture the authors found is of the order of magnitude that can be expected after induction of anesthesia [18]. Half of this venous admixture is caused by atelectasis resulting in absolute shunt, and the other half by dispersion of the distribution of perfusion to alveoli with low ventilation-perfusion ratios resulting in ventilation-perfusion mismatch.

Other investigators have found that increasing intra-abdominal pressure to 14 mm Hg with more moderate degrees of head-down (−20°) did not significantly modify physiologic dead space or venous admixture [16,19,20]. Even more surprisingly, Andersson and colleagues [21,22] found that, despite increasing atelectasis, CO_2 PP transiently reduces venous admixture, thereby increasing arterial oxygenation, a finding corroborated by other studies [23,24]. Why CO_2 PP increases arterial oxygenation despite increasing atelectatic lung area on CT by 66% (range, 11%–170%) has not been elucidated. Andersson and colleagues [21] suggest that the CO_2 PP might improve ventilation-

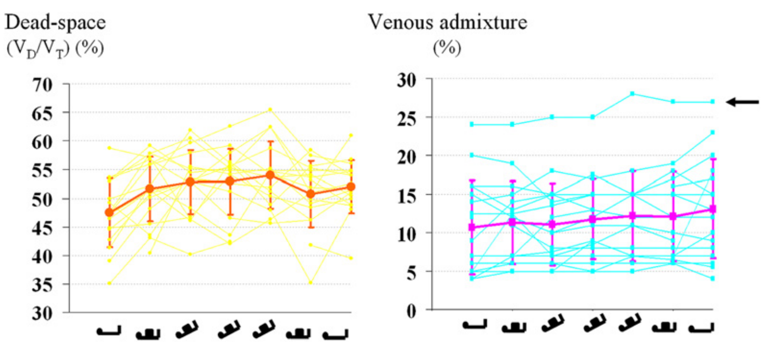

Fig. 6. Effects on dead-space ventilation and venous admixture. Dead-space ventilation (expressed as dead-space/tidal volume [V_D/V_T] [%]) and venous admixture. Thick lines with bars represent average and SD, respectively. Changes in dead-space ventilation are modest, and venous admixture did not change. Even in a patient with significant preexisting venous admixture (*arrow*), oxygenation did not worsen significantly. (*Data from* Schrijvers D, Mottrie A, Traen K, et al. Pulmonary gas exchange is well preserved during robot assisted surgery in steep Trendelenburg position. Acta Anaesthesiol Belg 2009;60(4):229–33.)

perfusion matching because the increased intra-abdominal pressure transmitted to the thorax could decrease perfusion in those areas where shunting was prevalent before PP. This theory is supported by a decreased dispersion of blood flow after induction of PP, which indicates better matching. Increased pulmonary capillary P_{CO_2} also enhances hypoxic pulmonary vasoconstriction.

It remains remarkable that lung function does not become more impaired under these nonphysiologic conditions. Even in a patient with a 25% venous admixture after induction of anesthesia (Fig. 6), venous admixture did not worsen after applying a PP or steep Trendelenburg position [17]. Although these results are reassuring and average gas exchange is unaltered, it should remain appreciated that there is considerable interindividual variability (Fig. 6) [25,26]. At some stage during the procedure, an individual patient may, therefore, benefit from a higher F_{IO_2}, an alveolar recruitment maneuver with or without the application of positive end-expiratory pressure (PEEP) (eg, after resuming the supine position), or an increase in minute ventilation. It is imperative to carefully monitor the arterial saturation with pulse oximetry and the end-expired CO_2 concentration and, if warranted, use arterial blood gas analysis to assess the alveolar-arterial O_2 and CO_2 gradients. Still, the intraoperative effects of CO_2 PP and steep Trendelenburg, in particular, on dead-space ventilation and venous admixture are small and should not be an obstacle to providing optimal surgical exposure by providing steep Trendelenburg position.

Whether or not to apply PEEP is somewhat unclear. Reasons not to apply PEEP are (1) the inconsistency with which low levels of PEEP have been proved effective [27–29]; (2) oxygenation is already improved by the CO_2 PP; (3) intrathoracic pressures increase further; and (4) venous drainage of the central nervous system (CNS) may be impeded. Although Valenza and colleagues [15] suggest PEEP be used, the value of recruitment maneuvers is being investigated.

Lung mechanics

The combination of a CO_2 PP and Trendelenburg alters ventilatory mechanics, mainly by decreasing thoracic compliance (Fig. 7) [14,15]. Although several strategies have been suggested to curb increases in peak and plateau inspiratory pressures, it is important to realize that (1) these pressures are measured at the mouthpiece and (2) do not reflect the pressure in the alveoli nor the transmural pressure across the alveoli. The bulk of the increase in airway pressures is caused by decreased thoracic wall compliance (due to pressure exerted by the CO_2 PP and the weight of the abdominal contents on the diaphragm) due to the head-down position–any changes in lung compliance are comparatively small. This is fortunate, because it implies that overdistention of the alveoli is not occurring despite the elevation seen in airway pressures. Alveoli are distended by an increase in transmural pressure across the alveolar (or lung) wall (transmural pressure = alveolar pressure − intrapleural pressure). Because the pressures in the pleural space and the alveoli are increased to the same degree (due to the decrease in thoracic wall compliance), lung transmural pressure and

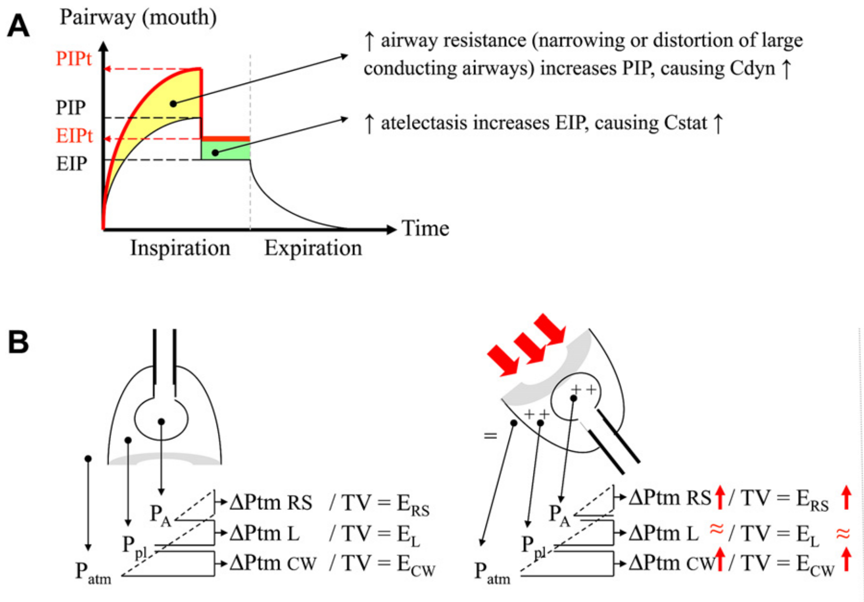

Fig. 7. The rise of airway pressure measured at the mouth is a poor descriptor of the mechanical derangement occurring during CO_2 PP. (*A*) When using controlled mechanical ventilation, applying CO_2 PP and head-down tilt causes a rise in both the peak inspiratory pressure (PIP) (because the large airways become distorted or narrowed) and the end-inspiratory (or plateau) pressure (EIP) (due to atelectasis), resulting in decreased dynamic (Cdyn) and static (Cstat) compliance. (*B*) These high airway pressures, however, do not pose the patient at risk of barotrauma or volutrauma because the transmural pulmonary pressure is unchanged. The increased airway pressure is the result of increased chest wall elastance (= E_{CW}) (or decreased chest wall compliance – elastance is the reciprocal of compliance) due to the pressure of the CO_2 PP and the weight of abdominal contents. The increased airway pressure (paw) is not the result of increased lung elastance (= E_L). Elastance of the entire respiratory system (RS) consisting of the sum of lungs (L) and the chest wall (CW) is increased ($E_{RS} = E_L + E_{CW}$), causing Paw to rise. Transmural gradients (ΔPtm) are calculated from the alveolar pressure (P_A), intrapleural pressure (P_{pl}), and atmospheric pressure (P_{atm}). Elastance is the ratio of the tidal volume (TV) and the ΔPtm under consideration. (*Data from* Valenza F, Chevallard G, Fossali T, et al. Management of mechanical ventilation during laparoscopic surgery. Best Pract Res Clin Anaesthesiol 2010;24(2):227–41.)

thus alveolar dimensions have not changed. Therefore, the high airway pressures as such do not have to be treated–ventilation can be continued with normal tidal volumes, and the airway pressures can often be followed without undue concern. Note that the decreased chest wall elastance is also contributory to the misleading high CVP values (discussed previously) (Fig. 8).

Still, absorption and elimination of exogenous CO_2 require additional ventilation, up to 30% to maintain normocapnia [16]. Any increase in end-expired CO_2 larger than 25% or occurring later than 30 minutes after the beginning of the CO_2 PP should suggest CO_2 subcutaneous emphysema [6].

To attenuate the peak airway pressure, during controlled mechanical ventilation, tidal volume may be decreased and respiratory rate and the duration of the inspiratory phase increased (eg, inspiratory-expiratory ratio from 1:2 to 1:1). Pressure-controlled ventilation may limit the inspiratory pressures, but the tidal volume becomes dependent on the constantly changing resistive and compliance characteristics of the lungs–careful titration relative to the end-expired CO_2 is mandatory if this approach is chosen.

The pressure-controlled volume guarantee or analogous ventilation mode available on some anesthesia machines uses software that adjusts the inspiratory flow pattern to deliver the required tidal volume with the lowest airway pressure possible. Somewhat surprisingly, this mode does not automatically manipulate the inspiratory-expiratory ratio, which is an important tool to attenuate airway pressures by allowing more inspiratory time.

No ventilation mode has been proved superior [30–32]. Although different ventilatory modes have been proposed, it is more important to understand

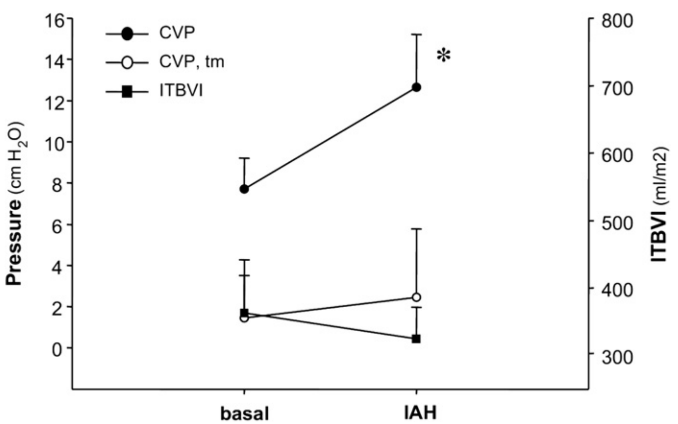

Fig. 8. The role of chest wall derangement on high CVP values during CO_2 PP. During intra-abdominal hypertension (IAH), CVP significantly rises whereas transmural pressure (CVP, tm) or intrathoracic blood volume (ITBVI) do not, underlying the role of chest wall derangement on artifactually and potentially misleading high CVP values during CO_2 PP. (*Data from* Valenza F, Chevallard G, Fossali T, et al. Management of mechanical ventilation during laparoscopic surgery. Best Pract Res Clin Anaesthesiol 2010;24(2):227–41.)

why the pressures increase and that the pressures at the mouthpiece do not reflect alveolar nor transmural lung pressure.

If maintaining isocapnia proves a challenge despite adjustments to the ventilator, P_ACO_2 can be allowed to rise (permissive hypercapnia), which is generally well tolerated for the duration of the procedure. This may be an option particularly with excessive resorption of CO_2 from the retroperitoneum. Although CO_2 resorption from within the peritoneum is modest, CO_2 that finds its way outside the peritoneum via the surgical site (the prostate is located outside the peritoneum) or in-between the peritoneum and the other structures making up the abdominal wall may lead to excessive exogenous CO_2 absorption that can strain the CO_2 removal capacity of the lungs (vide infra). Finally, the intraperitoneal abdominal CO_2 pressure may have to be decreased or temporarily released to briefly hyperventilate the patient and bring $Paco_2$ down to acceptable levels (exceptionally rare). Because the increase in $Paco_2$ depends on the intra-abdominal pressure, reducing it may help decrease $Paco_2$ [33].

CNS

Patients generally tolerate even prolonged episodes of CO_2 PP well: after several tens of thousands of patients have undergone a robot-assisted prostatectomy, the authors are aware of no reports of focal or global neurologic deficits. Why do patients tolerate even prolonged (>6 hours) exposure to the combination of combined CO_2 PP and steep Trendelenburg position so well?

First, CNS blood flow (CBF) is autoregulated (Fig. 9). Within certain limits of perfusion pressure, CBF remains constant because the diameter of the cerebral arterioles increases as CPP decreases. If CNS perfusion behaves like a Starling resistor (see Fig. 9), CPP is the difference between MAP and either CVP or intracranial pressure (ICP), depending on which is highest. The lower threshold of autoregulation is often cited as 50 mm Hg to 60 mm Hg (although these thresholds have been challenged) [34].

The authors have found that the average CPP (calculated as MAP − CVP) after assuming the Trendelenburg position remains within the limits, between which CBF is usually considered maintained by autoregulation [35]. Later, however, during the course of the procedure, CPP may drop well below 50 mm Hg in an occasional patient (Fig. 10). Even though an effect on outcome cannot be claimed, some anesthesiologists argue this is an indication to invasively monitor MAP and CVP. The authors use this information to guide administration of phenylephrine to restore CPP above 60 mm Hg. By positioning the transducer at the level of the ear canal, CPP can be directly calculated from the mean values displayed on the monitor. The high CVP and MAP values displayed on the monitors are not indicative of a sufficient filling status and perfusion pressure of more elevated organs, respectively.

Second, CO_2 PP increases ICP. This increase is independent of arterial pH, oxygenation, or MAP; it is seen even at low (8 mm Hg) abdominal pressures and is especially pronounced in animals with baseline elevated ICP [36–38].

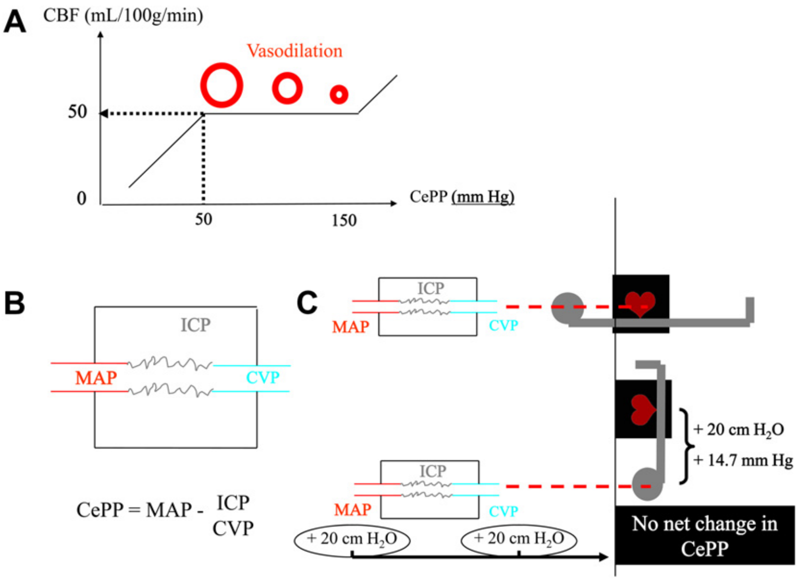

Fig. 9. Autoregulation, CPP, and positioning of pressure transducers. (*A*) Blood flow to the brain (CBF) is autoregulated within certain limits: as the cerebral perfusion pressure (CePP) decreases, cerebral vessels dilate, maintaining CBF. Below a CePP of 50 mm Hg, CBF decreases with CePP (even though the exact relationship is probably more complex, and varies between individuals). (*B*) If CNS perfusion is likened to a Starling resistor, CePP can be calculated as the difference between MAP and CVP or ICP, whichever is higher. MAP and CVP can be easily measured; CPP cannot be higher than the difference between these two (but it could be lower, if ICP is higher than CVP, although ICP is not measured). (*C*) If the pressure transducer is positioned at the ear canal, and the patient is placed head down, both MAP and CVP rise by an equal amount (eg, 20 cm H_2O or 14.7 mm Hg), resulting in no net change in CePP. The high MAP in and by itself may give a false sense of adequate perfusion pressure – the MAP at the level of the coronary arteries is 14.7 mm Hg lower.

Trendelenburg position worsens the increase in ICP during insufflation, but reverse Trendelenburg does not eliminate it [36]. The exact mechanism by which intraabdominal pressure affects ICP has not been elucidated, but it is probably multifactorial [39]. The Monro-Kellie doctrine states that the bony skull contains 3 elements: parenchymal tissue, arterial and venous blood, and cerebrospinal fluid in a dynamic equilibrium. With a rapid increase in the volume of any of these components, ICP rises. It has been proposed that increased intraabdominal and intrathoracic pressure as well as impaired cerebrospinal fluid absorption during insufflation impede drainage of the lumbar venous plexus and induce an increase in the vascular compartment of the sacral space, causing the rise in ICP [36,40]. Additionally, hypercarbia is known to cause cerebral vasodilation, which results in an increased ICP. If ICP does not increase, an increased transmural vascular pressure might render the intracerebral vessels prone to rupture.

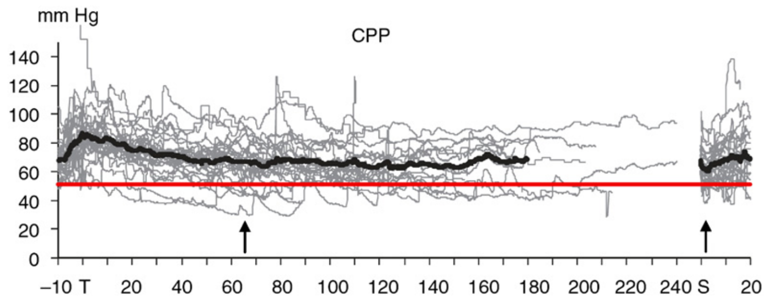

Fig. 10. Average CPP calculated as MAP – CVP remained within autoregulatory limits after assuming the Trendelenburg position. Later, however, during the course of procedure, CPP may drop well below 50 mm Hg in an occasional patient (see curves below red line). Even though an effect on outcome cannot be claimed, some anesthesiologists argue this is an indication to invasively monitor MAP and CVP. (*Data from* Kalmar AF, Foubert L, Hendrickx JF, et al. Influence of steep Trendelenburg position and CO2 pneumoperitoneum on cardiovascular, cerebrovascular, and respiratory homeostasis during robotic prostatectomy. Br J Anaesth 2010;104(4):433–9.)

Third, there are important surrogate outcome variables that indicate the brain tolerates the CO_2 PP and steep Trendelenburg position well. Using near-infrared spectrometry, the authors have found regional brain oxygenation well preserved (Fig. 11). During initiation of the surgery program at the authors' institution, a CT scan of the brain of one patient before and immediately after the procedure (<15 minutes) revealed no abnormalities (Fig. 12). No evidence was found of increased resistance to CBF, indicating that any cerebral edema that might have developed would be unlikely to affect cerebral perfusion [41]. In addition, the authors' preliminary findings of optic nerve sheath diameter

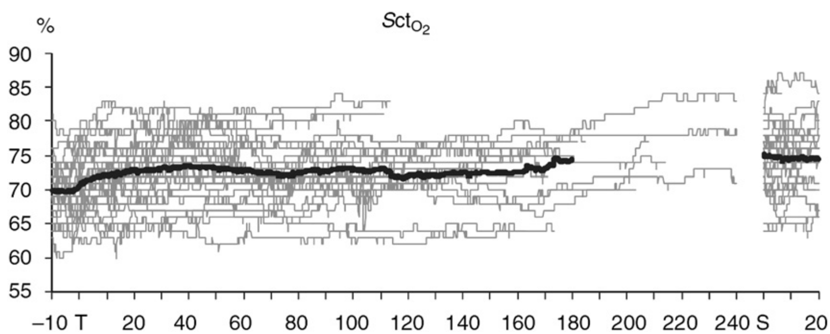

Fig. 11. Effects of CO_2 PP and head-down positioning on near-infrared spectroscopy. In 31 patients, regional cerebral tissue saturation (Sct_{O_2}) increased on average from 70% to 73%, after assuming the Trendelenburg position, and further increased to 74%, after resuming the supine position. (*Data from* Kalmar AF, Foubert L, Hendrickx JF, et al. Influence of steep Trendelenburg position and CO2 pneumoperitoneum on cardiovascular, cerebrovascular, and respiratory homeostasis during robotic prostatectomy. Br J Anaesth 2010;104(4):433–9.)

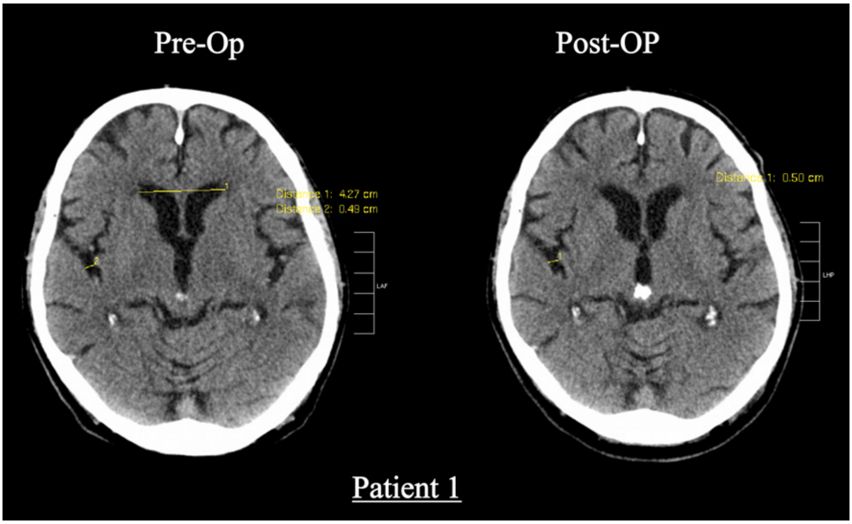

Fig. 12. CT scan of the brain. During initiation of the surgery program at the authors' institution, a CT scan of the brain of 3 patients before and immediately after the procedure (<15 minutes) revealed no abnormalities.

measurements (a well-documented indicator of increased ICP in the acute trauma setting) are reassuring.

Fourth, even though facial edema may develop, this is by no means indicative of intracerebral fluid kinetics. The blood-brain barrier helps prevent the development of interstitial edema in the CNS despite the increase of the hydrostatic pressure in the cerebral blood vessels. The composition of intracerebral capillaries (the blood-brain barrier) is entirely different from that of the extracranial capillaries (Fig. 13). Useful information can be gleaned from space research: the head-down position is used to simulate the conditions prevailing in space–weightlessness causes a fluid shift from the feet to the brain analogous to what happens during steep Trendelenburg. Animal data (rabbits) reveal congestion of only the pial vessels after 8 days of head-down tilt without any edematous changes of the cerebral neuronal tissues or any leakage of special markers through the vessel walls (Fig. 14) [42].

Even though many aspects remain incompletely understood, these findings are reassuring. The evidence supports that no special measures are needed in the belief that cerebral edema is developing during procedures in this position. There are limits, however, and common sense needs to guide clinical judgment in certain circumstances (eg, a 75-year-old male patient with a preoperative diagnosed space-occupying lesion in the medullary region should not undergo robotic radical cystectomy) [43]. The authors expect that any condition that may disturb the blood-brain barrier (such as brain tumors) carries unknown risks which the available data do not allow fully understanding or anticipating.

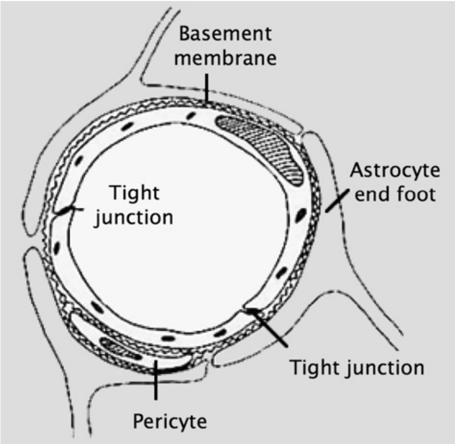

Fig. 13. Histology of the blood-brain barrier. The gaps between endothelial cells of the CNS are sealed by tight junctions. Pericytes and endothelial cells are completely encapsulated by basement membrane. Astrocytic end-feet envelop approximately 99% of all the vasculature.

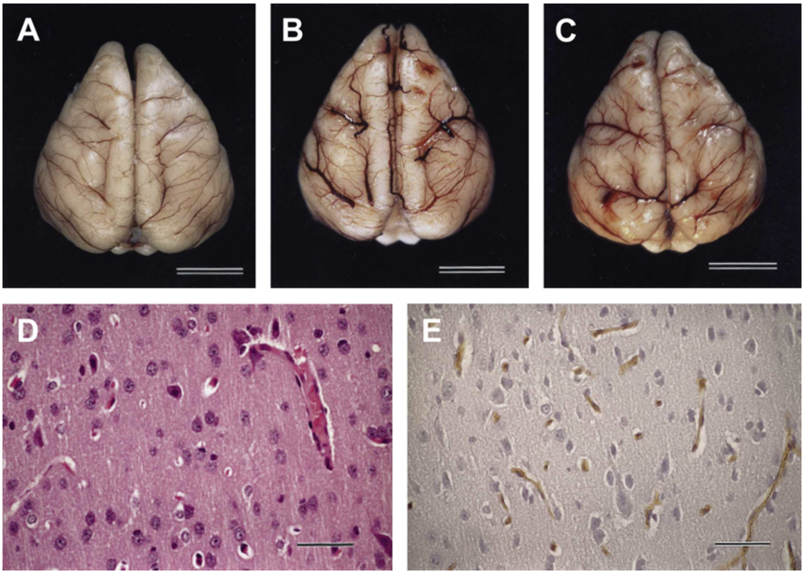

Fig. 14. Histopathology of the blood-brain barrier after 8 days of head-down tilt. Animal data (rabbits) reveal congestion of the pial vessels only after sustained (*A* = controll, *B* = after 2 days, *C* = after 8 days) head-down tilt , without any … neuronal tissues (light microscopical findings of the cortex in the frontal lobe excised from the 8-day head down tilt rabbit and stained with hematoxylin and eosin, *D*) or leakage of the special markers through the vessel walls (immunohistochemical staining of the cortex in the frontal lobe excised from the 8-day head down tilt rabbit, *E*). (*Data from* Shimoyama R, Miyata H, Ohama E, et al. Does edema formation occur in the rabbit brain exposed to head-down tilt? Jpn J Physiol 2000;50(1):141–7.)

Posterior ischemic optic neuropathy has been reported after minimally invasive prostatectomy, but the cause remains unclear. Although anamnesis should reveal ocular pathology during the preoperative interview, its value in preventing ocular complications in this setting is unclear. Even in patients with glaucoma or other ocular diseases, there has been no reported increased risk of perioperative ischemic optic neuropathy for procedures in the prone or Trendelenburg position [44]. Because the intraocular pressure increases, on average, 13 mm Hg by the end of Trendelenburg position compared with preinduction values, however, common sense dictates patients with glaucoma should continue their scheduled antiglaucoma medication.

Renal

Elevations of intra-abdominal pressure during laparoscopic procedures may lead to oliguria or anuria in mammals. Despite this, previous research has not been able to confirm an associated kidney injury and none could be found in a recent study where rats were exposed to a CO_2 PP of up to 4 hours: urine output was reduced but NGAL expression, a sensitive marker for renal injury, was not increased [45]. The authors are aware of no data on the renal effect of Trendelenburg position nor on its combined use with a CO_2 PP. Maintaining an adequate filling status and normal cardiac output seem to be the overriding goals to preserve renal function; under these conditions, urinary output is unlikely to be a predictor of postoperative renal dysfunction [46,47].

Choice of anesthetic agents

No particular drug regimen has been shown superior with regard to meaningful outcome in this population, and either a total intravenous technique or inhaled anesthetic technique can be used. Nitrous oxide is not specifically contraindicated–it does not interfere with surgical exposure [48] and it may promote a rapid emergence. Although there is always a risk of venous air embolism, it is not a contraindication for the use of nitrous oxide in these circumstances and none has been reported during robot-assisted laparoscopies.

Fluid management

Whether colloids should be preferred to crystalloids is speculative, but because facial edema resulting from head-down tilt in volunteers is caused primarily by elevated capillary pressures and decreased plasma colloid osmotic pressures [49], it may be wise to avoid overzealous administration of crystalloids.

Emergence and postoperative care

Postoperative agitation has been observed but remains poorly quantified, and the contribution of the CO_2 PP and Trendelenburg position is uncertain. Despite indirect evidence to the contrary, it has prompted some anesthesiologists to speculate that cerebral edema might be present and ventilate patient postoperatively arbitrarily for 1 hour. Arguing that an awake patient is the best neuromonitor, other investigators (JFAH) prefer to extubate the patients immediately postoperatively. The cause of postoperative agitation is probably multifactorial, and intensive postoperative analgesia and the administration of an anticholinergic drug to attenuate bladder spasm and the discomfort of the presence of a Foley catheter seems to have lessened its incidence in the authors' experience. Transversus abdominis plane blocks placed after induction of anesthesia may help provide additional postoperative analgesia. Readers may infer from the absence of references in this section that more questions remain than have been answered.

It is imperative to ensure that the airway can be maintained after extubation. Although facial and scleral edema is an important physical sign that can alert clinicians to the presence of airway edema, significant edema of pharyngeal tissue may not be accompanied by visible external signs. Laryngeal soft tissue edema may be assessed by performing a cuff leak test: gas should be able to flow past the endotracheal tube after deflating the cuff when a pressure of 15 cm H_2O is applied. Another option is to have the patient breathe spontaneously and to occlude the proximal end of the endotracheal tube after cuff deflation–the patient should ideally then be able to breathe around the tube. Postextubation respiratory distress may require reintubation and subsequent ventilation in an ICU [3]. The authors recommend that if the cuff leak test fails, patients should remain intubated until the edema has subsided. Other indications for (brief) postoperative ventilation may include excessive blood loss or excessive subcutaneous emphysema.

Furosemide may be prescribed by a urologist in an attempt to prevent blood clot formation in the urinary tract. Although the evidence to substantiate this practice is scant or nonexistent, its side effects are well documented: hypokalemia, hyperglycemia, hypovolemia, and loss of urinary output as an indicator of organ perfusion. If administered, appropriate fluid administration to compensate for excessive urine production and electrolyte loss should be considered.

Contraindications

The major contraindication is intracranial pathology associated with intracranial hypertension or disruption of the blood-brain barrier. In patients suffering from glaucoma, it is probably wise to ensure the ocular pressure has been well treated.

SUMMARY

Because of the excellent results, it can be predicted that an increasing number of patients will undergo robot-assisted procedures with CO_2 PP and steep Trendelenburg position. Fortunately, the human body has a remarkable yet incompletely understood capacity to withstand the effects of a CO_2 PP and steep Trendelenburg position during general anesthesia. Although individual responses vary and should be monitored, effects on most organs are modest and should not be an obstacle to providing optimal surgical exposure during robot-assisted prostatectomy, cystectomy, or hysterectomy. Pre-existing intracranial pathology (mass lesions and edema) needs to be excluded because it is currently the most significant absolute contraindication. Painstaking attention to positioning is of overriding importance. Continual awareness of the primary importance of coronary and CPPs, rather than the more common attention to

MAP, is fundamental to safeguard cardiac and cerebral perfusion. The interpretation of MAP needs to take the effects of height differences and site of pressure measurement into account. Further experience and study will refine the perioperative management, in particular with regard to ventilation strategies, fluid management, and postoperative analgesia.

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