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Effects of Prolonged Pneumoperitoneum on Hemodynamics and Acid–Base Balance during Totally Endoscopic Robot-assisted Radical Prostatectomies

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Abstract. Laparoscopic techniques have become a standard approach for diagnostic and therapeutic procedures in many surgical disciplines. Recent progress in endoscopic surgery is based on the integration of computer-enhanced telemanipulation systems. Because robot-assisted radical prostatectomies take up to 10 hours, the present study was performed to evaluate the effects of prolonged intraperitoneal CO_2 insufflation on hemodynamics and gas exchange in 15 patients with prostate cancer. When CO_2 insufflation was initiated, peak inspiratory pressure increased and reached significant values after a 1.5-hour period of intraperitoneal CO_2 insufflation. With the release of CO_2, peak inspiratory pressure decreased close to baseline values. A significant increase in heart rate was observed after a 4-hour period of increased intraabdominal pressure. Mean arterial blood pressure and central venous pressure remained stable during CO_2 insufflation. Minute ventilation was adjusted according to repeated blood gas analyses to maintain pH, base excess (BE), bicarbonate (HCO_3^-), and $PaCO_2$ within physiologic ranges. The present data show, that prolonged CO_2 insufflation during totally endoscopic robot-assisted radical prostatectomy results in only minor changes in hemodynamics and acid-base status. Because of the limited experience with long-term pneumoperitoneum, we consider invasive haemodynamic monitoring and repeat blood gas analysis essential for such operations.

Laparoscopic techniques have become a standard approach for diagnostic and therapeutic procedures in many surgical disciplines. In urology, radical prostatectomy can be performed with endoscopic techniques [1]. The computer-enhanced surgical system daVinci (Intuitive Surgical, Mountain View, CA, USA) is a recently developed technology that allows extremely precise and atraumatic surgery by telemanipulation. The surgeon operates this system while seated at a console that allows three-dimensional visualization of the surgical field. The system translates the movements of the surgeon's hands in the console real-time to specialized instruments positioned inside the patient through small puncture incisions. Software eliminates the tremor of the surgeon's hands.

Like many laparoscopic procedures, this technique requires CO_2 insufflation with positive pressure, to allow optimal visualization. Hemodynamic changes have been shown to result after 60 to 120 minutes of intraabdominal CO_2 insufflation [2–5]. The present study was performed to evaluate the effect of prolonged intraperitoneal CO_2 insufflation on hemodynamics and gas exchange in a prospective study, because operating times for robot-assisted radical prostatectomy are markedly longer than for the standard approach.

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Patients and Methods

After approval by the institution's ethics committee and informed written consent, fifteen patients (American Society of Anesthesiologists classification) ASA I–III underwent totally endoscopic radical prostatectomy with the da Vinci robotic system.

Anaesthesia

After oral premedication with 7.5 mg midazolam, anesthesia was induced intravenously with 0.5 μg kg^{-1} remifentanil, 2 mg kg^{-1} propofol, and 0.2 mg kg^{-1} mivacurium. After intubation, patients received controlled ventilation with oxygen 50% in air. The initial tidal volume was 8 to 10 ml kg^{-1} at a respiratory rate of 10 breaths per minute. Respiratory parameters were adjusted according to arterial blood gas status throughout the operation to maintain physiologic pH, base excess (BE), bicarbonate (HCO_3^-), and $PaCO_2$ (7.35 to 7.45, ± 3 mmol L^{-1}, 21 to 27 mmol L^{-1}, and 35 to 40 mmHg). For anaesthesia maintenance, propofol, remifentanil, and mivacurium were administered continuously and dosage was adjusted according to clinical status. Depth of anesthesia and muscle relaxation were assessed by additional neuromuscular (Innervator, Fisher & Paykel Auckland, New Zealand) and electroencephalographic monitoring (Narcotrend 2.0 AF/F, MT Monitor Technik, Bad Bramstedt, Germany). Intraoperative electrocardiographic (ECG) monitoring was performed with a 5-lead monitor and continuous ST segment analysis of leads I, II, and V5. Pulse oximetry and arterial blood pressure monitoring in the radial artery were employed. In addition, central venous pressure and esophageal temperature were monitored. To maintain body temperature, a heating blanket (Bair Hugger 505, Augustine Medical, Eden Prairie, MN, USA) was used. Postoperative analgesia was initiated with 7.5 mg piritramide and 1 g novaminsulfon 15 minutes before the end of surgery. After skin closure patients were either extubated in the operating room or transferred to the intensive care unit.

Surgical Technique

All patients were primarily in supine position. After cystoscopy and insertion of bilateral ureter stents transabdominal ports were placed and a pneumoperitoneum was created by CO_2 insufflation after moving the patient into a 30-degree Trendelenburg position. While the robot is positioned right next to the patient, the system is controlled via telemanipulation by a surgeon sitting at a remote console. The surgeon's assistant changes the instruments that are connected to the robotic arms and inserted through the ports. The operation continues with bilateral pelvic lymphadenectomy followed by immediate histological examination of the lymph nodes. After preparation and exposure of the prostate gland with consecutive urethral-vesical anastomosis, the prostate is removed via the medial port with consecutive release of the pneumoperitoneum. The operation is terminated by closure of the skin stab wounds.

Assessment of Outcome Variables

Arterial blood gas analysis including pH, BE, HCO_3^-, $PaCO_2$, and PaO_2 was performed in the operating room with an ABL3 Analyzer (Acid Base Laboratory/Hemoxymeter, Radiometer, Copenhagen, Denmark). The following data were obtained together with each blood gas analysis: minute ventilation (MV), peak inspiration pressure (PIP), intraabdominal pressure (IAP), heart rate (HR), mean arterial pressure (MAP), and central venous pressure (CVP). Baseline values were obtained prior to establishing a pneumoperitoneum with the patient in the Trendelenburg position. Further laboratory and physiological data collection was performed 10 and 30 minutes later (PP + 10, PP + 30) and at 30-minute intervals throughout the operation. Immediately after surgery with the patient still in the Trendelenburg position, a final assessment was made.

Statistical Analysis

All data are presented as mean ± standard deviation. Calculation and data analysis were performed using a statistical package (GraphPad InStat 3.0, GraphPad Software, San Diego, CA, USA). Statistical significance was determined with either the Friedman test and Bonferroni adjustment or the Wilcoxon-Mann-Whitney test. Differences were considered to be statistically significant if p was < 0.05.

Results

Fifteen patients with prostate cancer underwent radical prostatectomy performed endoscopically with the da Vinci telemanipulation system. Demographic and clinical data are presented in Table 1.

Table 1. Demographics and general data.

Age (years)	60 ± 2.9
Weight (kg)	84.5 ± 10.7
Height (cm)	177.5 ± 7.9
Duration of anaesthesia (minutes)	724.3 ± 93.6
Duration of surgery (minutes)	591.7 ± 85.8
Duration of pneumoperitoneum (minutes)	545.7 ± 79.3

Results are mean values ± SD.

Total intravenous anaesthesia was adjusted to anesthesia depth levels between D0 and E1 according to Kugler [6] as monitored with the Narcotrend system (Narcotrend, Bad Bramsted, Germany). During anesthesia, patients received 5,535 ± 1,025 ml lactated Ringer's solution and 2,100 ± 625 ml hydroxyethyl starch 6%. Two units of packed red blood cells were administered into a patient who received an additional 400 ml albumin 5%.

Heart rate and mean arterial pressure initially were not affected by the pneumoperitoneum. After a 4-hour pneumoperitoneum a significant increase in heart rate was observed. Mean arterial pressure remained stable during CO_2 insufflation. Central venous pressure underwent only minor changes during surgery; with CO_2 desufflation central venous pressure decreased and was postoperatively 24% below baseline value (p: n.s.) (Fig. 1a and b). Hemodynamic alterations were not of clinical relevance, and no catecholamines were required for hemodynamic stabilization. Significant ST segment changes were not observed throughout the entire operation.

During insufflation intraabdominal pressure was maintained around 12 mmHg (Fig. 1b). When CO_2 insufflation was initiated, peak inspiratory pressure increased and reached significant values after a 1.5-hour period of intraabdominal CO_2 insufflation. With the release of CO_2, peak inspiratory pressure decreased close to baseline (p: n.s.) (Fig. 2a).

$PaCO_2$ increased during the initial 90 minutes of CO_2 insufflation and reached a plateau that was significantly higher than baseline and remained constant throughout the operation. Even after CO_2 desufflation, $PaCO_2$ remained significantly elevated (Fig. 3a). Minute ventilation was increased parallel to the rise of $PaCO_2$. Even after surgery a markedly elevated MV was required to maintain pH, BE, HCO_3^-, and $PaCO_2$ within physiologic ranges (Fig. 2a, 3a–d). PaO_2 was not significantly affected by the pneumoperitoneum, but it decreased below baseline after CO_2 desufflation (p: n.s.) (Fig. 2b).

Body temperature dropped 0.07°C during initial CO_2 insufflation and increased by 0.18°C per consecutive hour. Mean body temperature at the end of surgery measured 37.0°C.

Extubation was achieved immediately after the operation in seven patients, while the remaining eight were extubated 40 to 545 minutes later in the ICU (median: 400 minutes).

Discussion

Minimally invasive surgery has seen tremendous growth after the first laparoscopic cholecystectomy was performed by Phillippe Mouret in 1988. First reports on a laparoscopic radical prostatectomy were published in 1992 [1] and were followed by growing experience with this technique to treat carcinoma [7–9]. Recent progress in endoscopic surgery is based on the integration of computer-enhanced telemanipulation systems such as the daVinci technology employed in the present study. The visualization sys-

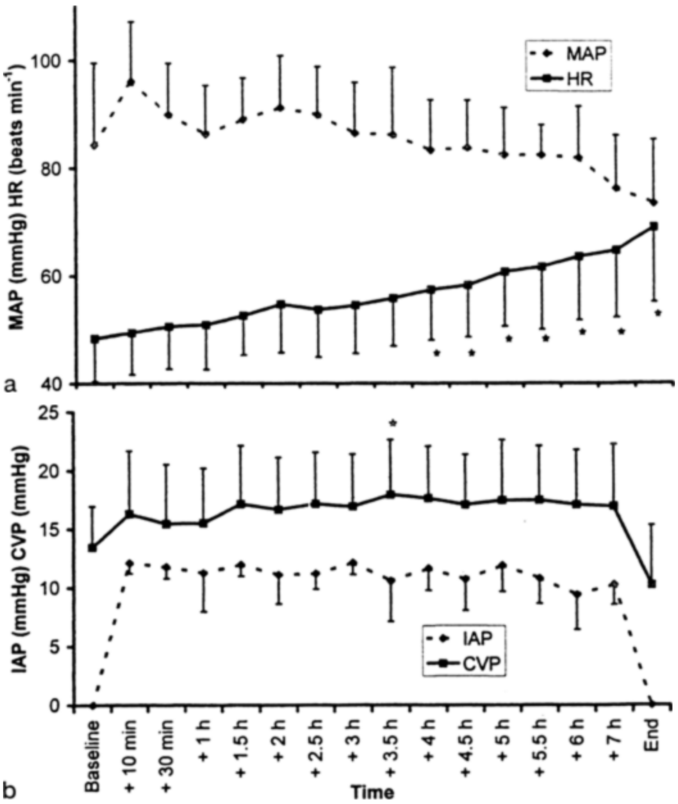

Fig. 1. a. Changes in mean arterial blood pressure (MAP) and heart rate (HR) from preinsufflation (baseline) phase, during pneumoperitoneum (+ 10 minutes–7 hours), and at its withdrawal (end). Data are presented as mean ± SD. Difference from baseline: $^*p < 0.05$. **b.** Changes in intraabdominal cavity pressure (IAP) and central venous pressure (CVP) from preinsufflation (baseline) phase, during pneumoperitoneum (+ 10 minutes–7 hours), and at its withdrawal (end). Data are presented as mean ± SD. Difference from baseline: $^*p < 0.05$.

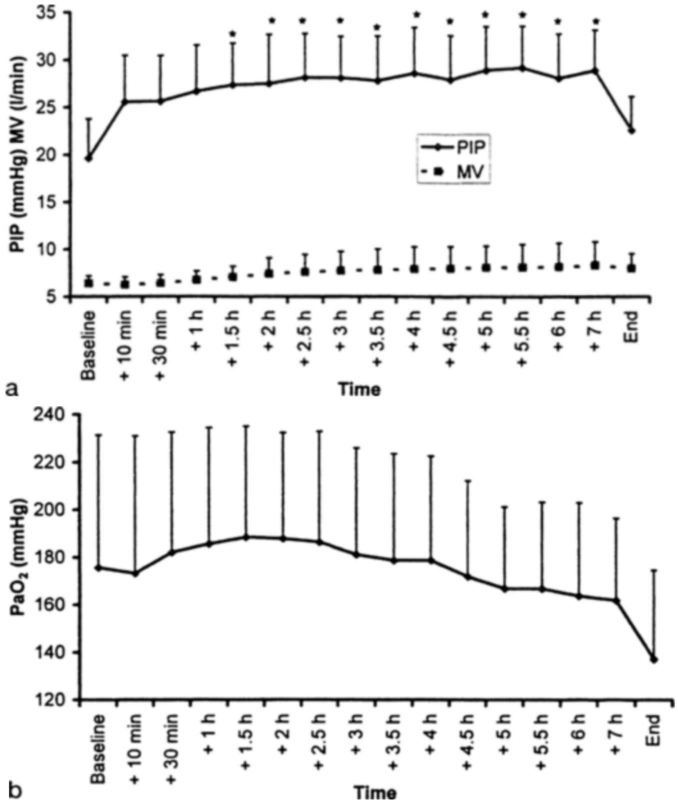

Fig. 2. a. Changes in peak inspiratory pressure (PIP) and minute ventilation (MV) from preinsufflation (baseline) phase, during pneumoperitoneum (+ 10 minutes–7 hours), and at its withdrawal (end). Data are presented as mean ± SD. Difference from baseline: $^*p < 0.05$. **b.** Changes in arterial O_2 pressure (PaO_2) from preinsufflation (baseline) phase, during pneumoperitoneum (+ 10 minutes–7 hours), and at its withdrawal (end). Data are presented as mean ± SD.

tem in the master console offers a high-resolution three-dimensional view of the operative field with tenfold magnification. This allows greatly enhanced visualization of anatomic structures. Therefore this system may allow radical prostatectomy while maintaining continence and sexual potency.

Longer operating times are a potential disadvantage of this approach. Mean operating time in this initial cohort amounted to almost 10 hours. The literature states operating times between 3 and 7.5 hours for laparoscopic radical prostatectomy without pelvic lymphadenectomy. The addition of lymphadenectomy would increase operating times to 3.5 to 9.5 hours [10], which is comparable to the data in the present cohort.

In recent years numerous studies have documented the impact of the CO_2 pneumoperitoneum on acid-base balance and hemodynamic variables. Most data were obtained from laparoscopic cholecystectomies, short gynecologic operations, or animal studies [3, 5, 11–13]. Experience with long-term pneumoperitoneum is very limited, and only few reports have been published [14]. In addition, many studies were conducted with the patient in the reverse Trendelenburg position, which makes data comparison with our study difficult.

The present data show that maintenance of intraabdominal CO_2 pressure of 12 mmHg in Trendelenburg position for several hours does not affect mean arterial blood pressure in a clinically significant manner. However, the slight decrease in blood pressure, along with a parallel increase in heart rate may suggest progressive intravascular hypovolemia during the course of surgery. Estimation of volume status is somewhat difficult during such operations: central venous pressure, as a marker for right atrial filling depends on intraabdominal pressure and therefore cannot be relied upon. Similar problems are encountered when a pulmonary artery catheter is used to determine volume status by means of pulmonary capillary wedge pressure measurement. In addition, fluid loss due to perspiration and hemorrhage is difficult to estimate, as is urinary output after dissection of the urethra. A reliable determination of volume status can be achieved with transesophageal echocardiography (TEE). However, TEE requires additional specially trained staff.

There is no consensus in the literature regarding the effect of increased intraabdominal pressure in hypovolemic patients. Some describe marked reduction of stroke volume and impaired acid-base status [15], whereas other reports document the safety of laparoscopic surgery in the presence of hypovolemic shock, when extended cardiovascular monitoring and adequate anesthesia management are provided [16].

In contrast to the present data, Giebler and colleagues [2]

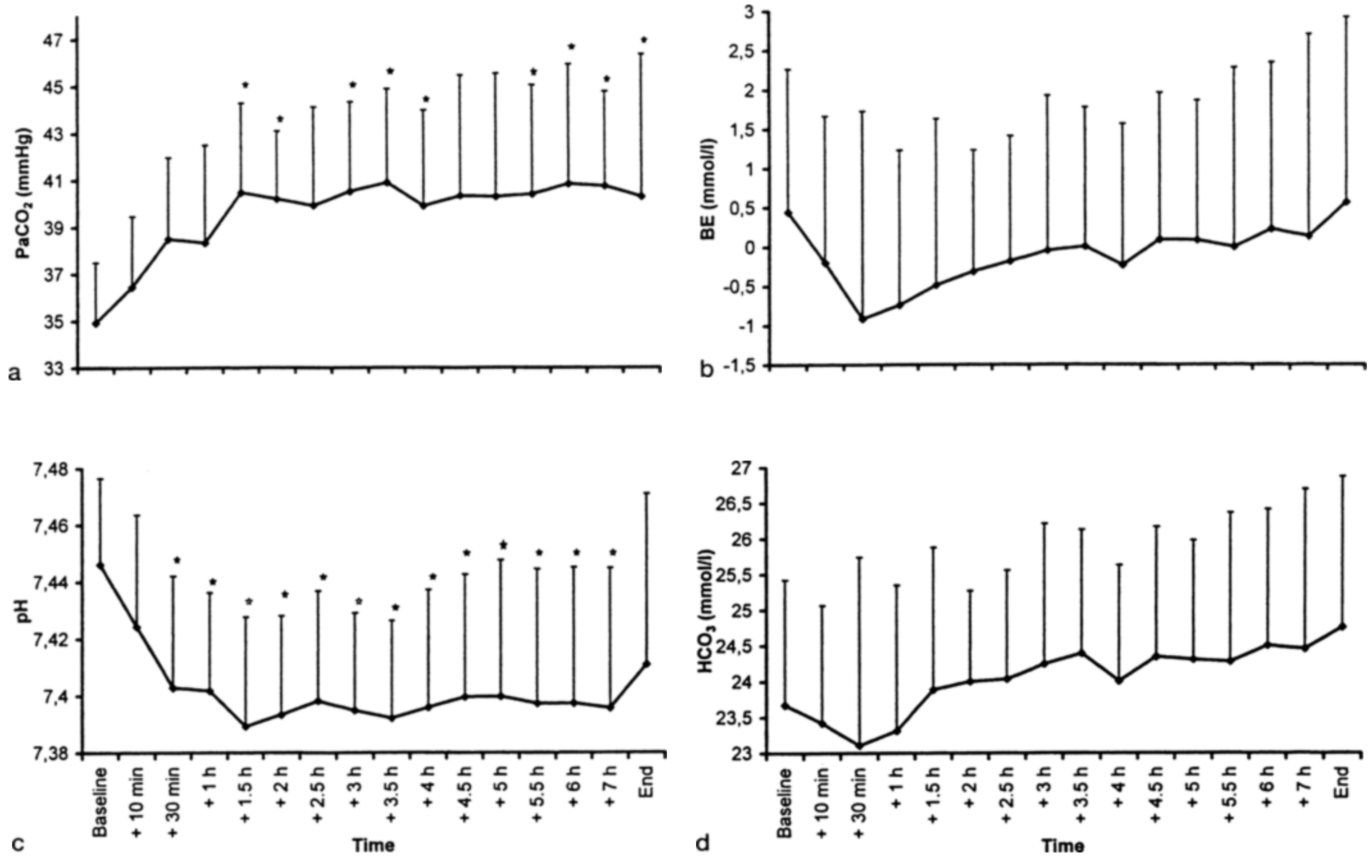

Fig. 3. **a.** Changes in arterial CO_2 pressures ($PaCO_2$) from preinsufflation (baseline) phase, during pneumoperitoneum (+ 10 minutes–7 hours), and at its withdrawal (end). Data are presented as mean ± SD. Difference from baseline: $^*p < 0.05$. **b.** Changes of pH from preinsufflation (baseline) phase, during pneumoperitoneum (+ 10 minutes–7 hours), and at its withdrawal (end). Data are presented as mean ± SD. Difference from baseline: $^*p < 0.05$. **c.** Changes in base excess (BE) from preinsufflation (baseline) phase, during pneumoperitoneum (+ 10 minutes–7 hours), and at its withdrawal (end). Data are presented as mean ± SD. **d.** Changes of bicarbonate (HCO_3^-) from preinsufflation (baseline) phase, during pneumoperitoneum (+ 10 minutes–7 hours), and at its withdrawal (end). Data are presented as mean ± SD.

reported increased MAP and unaffected heart rate after CO_2 insufflation with patients in the supine position. Increased sympathoadrenergic activity caused by enhanced CO_2 absorption via the peritoneum was linked to increased MAP and heart rate by Dexter et al. [17]. Further reports showed increased stroke work resulting in enhanced myocardial oxygen consumption during hypercapnia [18]. Especially elderly patients and those with a history of cardiac disease may be at risk for myocardial ischemia, which was not observed in the present cohort by means of continuous ST segment analysis.

The above conclusions regarding hemodynamic stability are limited by the fact that cardiac output was not determined in the present cohort, and the absence of myocardial ischemia was documented only by ST segment analysis, but not with transesophageal echocardiography. Despite reasonably stable hemodynamics in the present cohort, we believe that, besides basic hemodynamic monitoring with invasive blood pressure and central venous pressure monitoring, a pulmonary artery catheter or TEE may be useful to accompany the initial experience with new surgical techniques.

In our patients minute ventilation was adjusted according to repeated blood gas analyses in order to prevent hypercapnia. However, this could not prevent significantly increased arterial CO_2 pressure; which therefore remained within the normal physiologic range. A significantly elevated arterial CO_2 pressure even after release of the pneumoperitoneum can be attributed to the considerable amounts of CO_2 possibly stored in extravascular compartments of the body that are slowly redistributed and metabolized or exhaled. This report shows that extended duration of a pneumoperitoneum at 10 to 12 mmHg when in the Trendelenburg position, despite reduced functional residual capacity and potential atelectases, does not affect intraoperative acid-base balance in a clinically significant manner. Peak inspiratory pressure increased significantly after CO_2 insufflation, which may be related to the cranial displacement of the diaphragm due to the patient's position and increased intraabdominal pressure, as well as to enhanced MV resulting in further increase of inspiratory pressure [19].

Like conventional laparoscopic surgery, computer-enhanced telemanipulation results in reduced body temperature with intraabdominal CO_2 insufflation at room temperature [20]. The present patients received external warming with an air-heated blanket (Bair Hugger), that allowed compensation for any decline in body temperature despite the long operation.

As long as a patient is connected to the robotic arms via transabdominal ports, even small movements of the patient must be prevented. For this reason all patients in this cohort underwent complete relaxation by continuous infusion of mivacurium under neuromuscular monitoring. Even though the robotic instruments were removed from the patients only a few minutes before the end of the operation, followed by skin closure of the ports, this anesthesia regimen, together with remifentanil and propofol, allowed extubation of the seven most recent patients immediately after surgery. Eight of the initial nine patients in this series were extubated within 10 hours after surgery in the ICU. The decision not to extubate these eight patients immediately after surgery was based primarily on safety considerations associated with inexperience with the new surgical procedure, and not medical indications, such as hemodynamic instability, impaired respiratory function, or incomplete neuromuscular recovery.

The present data show, that prolonged CO_2 insufflation during totally endoscopic radical prostatectomy with the da Vinci telemanipulation system results only in minor changes in hemodynamics and acid-base status. It is important to note, however, that an excellent line of communication between anesthesiologist and surgeon is essential to provide optimal information on the course of the operation and the patient's condition. The prospect of substantial improvement in endoscopic surgery by robot-assisted techniques should not cloud our vision of potentially undesirable effects of this technique. Problems and complications cannot be conclusively documented in this, the first cohort reported to date.

Résumé. La technique laparoscopique est devenue le standard pour beaucoup de procédés diagnostiques et thérapeutiques dans diverses disciplines chirurgicales. De progrès récents en chirurgie endoscopique sont basés sur l'intégration de systèmes de la télémanipulation sur ordinateur. Puisque à présent, les prostatectomies radicales assistées par robot peuvent durer jusqu'à 10 heures, cette étude a été entreprise pour évaluer les effets de l'insufflation intrapéritonéale prolongée par le CO_2 sur l'hémodynamique et les échanges gazeux chez 15 patients porteurs de cancer de la prostate. Au début de l'insufflation par le CO_2, la pression inspiratoire maximale a augmenté et a atteint des valeurs significatives après 1.5 heures d'insufflation intrapéritonéale. Lorsque l'on a arrêté l'insufflation par le CO_2, la pression inspiratorie maximale a diminué pour se rapprocher des valeurs de base. On a observé une augmentation significative de la fréquence cardiaque après 4 heures d'hyperpression intra-abdominale. La pression artérielle moyenne et la pression veineuse centrale sont restées stables pendant l'insufflation par le CO_2. La ventilation minute a été ajustée selon les analyses des gaz du sang répétées pour maintenir le pH, la base-excès, les taux de HCO_3^- et de $PaCO_2$ dans les limites de la normale. Nos données actuelles nous montrent que l'insufflation prolongée de CO_2 pendant la prostatectomie radicale endoscopique assistée par robot ne modifie que peu l'état hémodynamique et l'équilibre acido-basique. En raison d'une expérience limitée en ce qui concerne le pneumopéritoine prolongé, nous considérons que le monitorage hémodynamique invasif et l'analyse répétée des gaz du sang sont essentiels pour de telles opérations.

Resumen. En muchas especialidades quirúrgicas las técnicas laparoscópicas se han convertidomen en procedimientos estándar tanto con fines diagnósticos como terapéuticos. Progresos recientes han permitido integrar la cirugía endoscópica en sistemas computarizados propiciando las técnicas de telecirugía y telemanipulación. Dado que la prostatectomía radical con ayuda de un robot dura más de 10 horas, estudiamos los efectos de un neumoperitoneo prolongado con CO_2 en la hemodinamia e intercambio gaseoso en 15 pacientes con cáncer de próstata. Al iniciar la insuflación de CO_2 la presión inspiratoria aumenta y alcanza valores significativos a las 1–5 horas de la instauración del neumoperitoneo. Cuando éste desaparece la presión inspiratoria máxima desciende a nivel basal. La presión arterial media (MAP) y la venosa central (PVC) se mantienen estables durante el neumoperitoneo. La ventilación minuto ha de ajustarse de acuerdo con gasometrías repetidas para mantener dentro de límites normales el pH, BE, HCO_3^- y la $PaCO_2$. Nuestros hallazgos demuestran que el neumoperitoneo prolongado por prostatectomía radical asistida mediante un robot produce cambios mínimos hemodinámicos y del equilibro ácido-base. Dada la corta experiencia con neumoperitoneo de larga duración, en estas operaciones son obligatorios la monitorización invasiva hemodinámica y frecuentes análisis gasométricos.

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