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COMPARATIVE STUDY OF PRESSURE-CONTROLLED VENTILATION VS. VOLUME-CONTROLLED VENTILATION IN ROBOTIC-ASSISTED NEPHRECTOMIES: EFFECTS ON RESPIRATORY MECHANICS AND HEMODYNAMICS

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Abstract

Introduction: Robotic-assisted nephrectomies require effective ventilation strategies due to pneumoperitoneum and Trendelenburg positioning, which significantly affect respiratory mechanics and hemodynamics.

Objective: To compare the effect of pressure-controlled ventilation (PCV) with that of volume-controlled ventilation (VCV) on the intraoperative respiration and hemodynamic values during robotic-assisted nephrectomies.

Material and Method: The randomised controlled trial was done between June 2024 and November 2024 at the Sindh Institute of Urology and Transplantation. Sixty patients were randomised into two groups (PCV and VCV, n=30 each). Peak inspiratory pressure (PIP), plateau pressure (Pplat), SpO, etCO, heart rate (HR) and mean blood pressure (MBP) were measured using four time points.

Results: The values of PIP and Pplat were substantially reduced during PCV than VCV, with a p value of <0.05. The PCV group was more hemodynamically stable, especially MBP. The two groups demonstrated similar oxygenation and CO 2 clearance.

Conclusion: PCV offers better airway pressure management and hemodynamic stability compared to VCV, making it preferred for robotic nephrectomies.

Keywords: Pressure-controlled ventilation, Volume-controlled ventilation, Robotic nephrectomy, Respiratory mechanics, Hemodynamics.

INTRODUCTION

The application of robotic-assisted methods has enhanced the accuracy and success of complicated urology surgeries like nephrectomies significantly. Nevertheless, these procedures always involve considerable physiological disturbances, especially because of the pneumoperitoneum and the acute Trendelenburg that has to be used during the surgery. These diseases trigger sequences of hemodynamic and respiratory disturbances, which introduce difficulties to anaesthetic and mechanical ventilation efforts. The appropriate choice of ventilatory mode is therefore central to achieving optimal respiratory mechanics and stability of hemodynamics during robotic-assisted nephrectomies (1). The two primary ventilation modes are volume-controlled ventilation (VCV) and pressure-controlled ventilation (PCV). VCV delivers a predefined tidal volume regardless of the amount of pressure needed and could result in raised peak airway pressures, especially in cases where the compliance of the lungs is decreasing due to pneumoperitoneum and the changing postures (2). However, PCV permits a fixed peak inspiratory pressure, which makes it easier to manage airway pressures and theoretically limits the likelihood of barotrauma at the expense of ensuring sufficient ventilation, through regulation of flow (3). The surgical and physiological peculiarities of robotic nephrectomies make the study of the effects of these ventilatory modes on the intraoperative respiratory and hemodynamic values warranted. Current literature reports sandwiched findings on the superiority of either mode. A meta-analysis by Schick et al. of the use of volume-guaranteed pressure-controlled ventilations versus volume-controlled ventilations during elective surgeries showed that there were lower peak airway pressures using pressure-controlled modes associated with a variable effect on both gas exchange and hemodynamics (4). Likewise, Chowdhury et al. reported an improvement of the respiratory dynamics under pressure-controlled volume-guaranteed ventilation to that of conventional modes during laparoscopic cholecystectomy (5). This distinction is more pertinent in the case of robotic-assisted nephrectomies, as a result of an exaggerated intrathoracic pressure swing and displacement of the diaphragm.

Mechanical power, which is the energy that is supplied to the respiratory system, is a new parameter that is being used to analyze the effects of various ventilation modes. Rietveld et al. showed PCV tends to provide lower mechanical power than volume-controlled modes, which may lessen injury to a lung due to ventilator action (6). Similar evidence was supported by Dhakshinamurthy and Singam during a study comparing the two in laparoscopic surgery, which reported the former reduced peak airway pressures and increased lung compliance (7). The advantages can be carried to robotic nephrectomies, where lung-protective manoeuvres are necessary to combat the positioning of the procedure. Gas exchange is also affected by ventilatory mode selection. Ammar et al. provided the same oxygenation and reduced end-tidal CO 2 levels using PCV-volume guaranteed modes in one-lung ventilation (8). Findings supported by Soliman et al., who demonstrated enhanced dynamic compliance and performance in ventilation using pressure-based modes in obese patients during laparoscopy (9).

Nonetheless, VCV can have unstable alveolar ventilation with patients who have abnormal respiratory mechanics, such as the situation during an extended robotic surgery. Besides the respiratory parameters, hemodynamic consequences of ventilatory modes matter. Fuest et al found that VCV induced larger hemodynamic fluctuations when CPR simulations were performed and PCV produced less varied pressure profiles (10). According to Takaoka et al., PCV restrains sudden increases in intrathoracic pressure, which improves the venous return and minimizes adverse cardiovascular consequences that often accompany high-volume ventilation strategies (11). These data are especially applicable in cases of nephrectomy patients who require cardiovascular stability during the perioperative period since this is paramount to renal perfusion and postoperative care.

The prone and Trendelenburg positions associated with robotic nephrectomies also contribute to the presence of ventilation-perfusion abnormalities and decreased thoracic compliance. A meta-analysis study by Han et al. that compared PCV and VCV during prone-position spine procedures demonstrated a significant benefit in PCV with regards to reduced airway pressures and increased efficiency of gas exchange (12). Moreover, Nasrolahzadeh et al. showed that PCV led to more stable endotracheal tube cuff pressures, which indirectly indicated less variability in airway pressure, which is beneficial in long and high intra-abdominal pressure surgery (13). There has also been variance in pediatric and geriatric response to these ventilation methods. In the study of Wang et al., which examined infants during thoracoscopic operations, PCV with volume guarantee has been determined to provide safer pressure profiles that preserved oxygenation (14). Likewise, Wang et al. in elderly patients who had undergone laparoscopic surgeries noted lower airway pressures accompanied by enhanced compliance in PCV-volume assured strategies (15). These data indicate the generalised advantage of pressure-controlled strategies on both age and surgical procedure.

Hemodynamically, Hasan and Haider have reported that the mean arterial pressures and heart rates were more stable at PCV compared to VCV in laparoscopic cholecystectomies, which are applicable in terms of perfusion of organs during renal procedures (16). Similar findings were reported by Sevdi et al. in the framework of bariatric surgery, as PCV maintained superior respiratory mechanics and reduced the cardiovascular load (17). Pournajafian et al. added to this view by showing lower peak pressures and better respiratory compliance in the PCV assurance in patients who have undergone laparoscopic bariatric surgery (18). Although a lot of information on laparoscopic surgery and open procedures has been offered, few studies focusing on robotic-assisted nephrectomies are available. The special requirements of robotic nephrectomy, as it involves prolonged operative time, intra-abdominal insufflation pressures and extreme positioning, place specific ventilatory demands on the patient. Therefore, this study proposes to address this lacking knowledge by comparing PCV and VCV in the context of robotic-assisted nephrectomies, and specifically their impact on respiratory mechanics and hemodynamics.

Objective: To determine the difference in the impact of pressure-controlled ventilation and volume-controlled ventilation on the intraoperative respiratory mechanics and hemodynamic stability of patients who underwent robotic-assisted nephrectomies under general anaesthesia.

MATERIALS AND METHODS

Study Design: Single-Blinded, Randomized Controlled Trial.
Study setting: The study was conducted at the Sindh Institute of Urology and Transplantation (SIUT), a tertiary care center specializing in robotic urological surgeries.

Duration of Study: The study was carried out over a six-month period from June 2024 to November 2024.

Inclusion Criteria: The patients in the age range of 18-70 years, who can be assigned to American Society of Anesthesiologists (ASA) physical status I-II and have a body mass index of 18-30 kg/m 2, have been considered to take part in the study. Elective robotic-assisted nephrectomy in general anaesthesia was going to be applied to the entire sample.

Exclusion Criteria: Those persons with a BMI greater than 30kg/m, past history of chronic obstructive pulmonary disease (COPD), asthma, or cardiovascular diseases, neuromuscular disorders, or absence of a general anaesthesia were also excluded.

Methods

The randomization of 30 patients each in Group PCV (pressure-controlled ventilation) and Group VCV (volume-controlled ventilation) took place after the consent and ethical approval of 60 qualified patients. A computer-generated sequence was used to carry out the randomization, and the patients were subjected to group allocation. Propofol (1.5-2.5 mg/kg), nalbuphine (0.1-0.2 mg/kg) and atracurium (0.5-0.6 mg/kg) were utilized to establish general anaesthesia. Isoflurane (0.5-1.5 MAC) was used to provide anaesthesia, and the inspired oxygen concentration was 40%. The parameters used in ventilation in the VCV group were I:E ratio at 1:2, tidal volume of 7 mL/kg, and respiratory rate was to keep $EtCO_2$ within 30-35 mmHg. Inspiratory pressure was altered in PCV to have identical tidal volume. Baseline (T1), 30 minutes (T2), 60 minutes (T3) and post-desufflation (T4) values of respiratory (PIP, Pplat, SpO_2, $EtCO_2$) and hemodynamic (HR and MBP) parameters were noted. SPSS version 22 was used to analyze data.

RESULTS

There were 60 patients who participated in the research and successfully underwent the procedure without any deviation from the protocol. The population geometry of the two groups was also similar, and their age, gender distribution and body mass index (BMI) had no statistically significant difference, proving that the randomisation was sufficient.

Table 1: Demographic Data

Variable	PCV Group (n=30)	VCV Group (n=30)	p-value
Age (years)	45.2 ± 12.3	43.8 ± 11.7	0.64
Sex (M/F)	16/14	18/12	0.61
BMI (kg/m²)	25.1 ± 2.8	26.3 ± 3.1	0.11

Intraoperative respiratory mechanics revealed that peak inspiratory pressure (PIP) and plateau pressure (Pplat) were significantly lower in the PCV group compared to the VCV group at all recorded time intervals. At T2 (30 minutes post-insufflation), the mean PIP was 21.1 ± 2.3 cmH_2O in the PCV group and 25.6 ± 3.1 cmH_2O in the VCV group ($p < 0.01$). Similarly, at T3 (60 minutes), the mean Pplat in the PCV group was 18.4 ± 1.9 cmH_2O compared to 22.1 ± 2.4 cmH_2O in the VCV group ($p < 0.05$), indicating improved lung compliance in the PCV group.

Table 2: Respiratory Pressures Over Time

Time Point	Group	PIP (cmH_2O)	Pplat (cmH_2O)
T1 (Baseline)	PCV	17.6 ± 2.0	15.2 ± 1.8
T1	VCV	19.2 ± 2.3	17.4 ± 2.1
T2 (30 min)	PCV	21.1 ± 2.3	17.9 ± 2.0
T2	VCV	25.6 ± 3.1	21.5 ± 2.7
T3 (60 min)	PCV	22.0 ± 2.4	18.4 ± 1.9
T3	VCV	26.8 ± 3.0	22.1 ± 2.4
T4 (Post-op)	PCV	18.5 ± 2.1	16.0 ± 1.6
T4	VCV	21.7 ± 2.6	19.4 ± 2.2

The two groups had comparable heart rates during the procedure without any statistically significant change in terms of hemodynamic stability. However, the mean blood pressure (MBP) was more stable in the PCV group, especially by way of pneumoperitoneum, and the statistical significance was found at T3 ($p = 0.03$). The parameters of gas exchange (SpO_2 and $EtCO_2$) were at the clinically acceptable levels in both groups. The improvement in oxygenation and the more regulated elimination of CO2 that was observed in PCV was not significant ($p > 0.05$).

Table 3: Gas Exchange and Hemodynamic Parameters

Parameter	PCV Group	VCV Group	p-value
SpO_2 (%)	98.5 ± 0.8	97.9 ± 1.2	0.22
$EtCO_2$ (mmHg)	36.2 ± 2.1	37.5 ± 3.0	0.09
HR (bpm)	78.4 ± 5.2	79.3 ± 6.0	0.44
MBP (mmHg at T3)	85.1 ± 4.5	81.0 ± 5.2	0.03*

Conclusively, pressure-controlled ventilation yielded lower airway pressures and less variable blood pressure during robotic nephrectomy and similar gas exchange as volume-controlled ventilation.

Discussion

The study was conducted to determine the comparison in the effects of pressure-controlled ventilation (PCV) and volume-controlled ventilation (VCV) on the respiratory mechanics and stability of hemodynamics in patients who had robotic-assisted nephrectomies. This randomised controlled trial was helpful in demonstrating the fact that PCV is highly beneficial in relation to reduction of airway pressures, besides offering hemodynamic stability during the intraoperative period, along with no difference being observed between both modes in terms of provision of oxygenation, besides carbon dioxide elimination. The most outstanding result of this research was the dropping of the values of peak inspiratory pressure (PIP) and plateau pressure (Pplat) that waxed steadily throughout all the recorded time in the PCV group. These findings are in agreement with earlier information, which demonstrated PCV being related to improved compliance of the lungs and lowered airway pressure, due to its slowing down of the course of flow and pressure-limiting effects (1). Veerasamy et al. compared PCV versus VCV at randomisation during robotic abdominoplasty and found that the arterial to end-tidal CO2 gradient was smaller with PCV, indicating greater efficiency of ventilation (1).

Similarly, Khater et al., in an analysis of obese patients receiving robotic urologic implantation, asserted that airway pressure should be reduced in order to ensure that postoperative pulmonary problems would not occur, which would be more easily achieved using PCV (2). Respiratory and cardiovascular stress is worsened by the physiological demands of robotic nephrectomy, such as the steep Trendelenburg position and pneumoperitoneum. This quality of PCV shows a better adaptability in such settings with a superior ventilational distribution and less risk of barotrauma. Lambertini et al. have found better respiratory mechanics by studying the comparative analysis of the types of access in robots, which adds more evidence to the efficacy of PCV in such situations (3). The conclusion of the meta-analysis conducted by Schick et al. supports findings when stating that pressure-targeted ventilation leads to reduced PIP and increased lung compliance in elective surgeries (4).

In the case of the gas exchange, both modes of ventilation maintained suitable SpO 2 and end-tidal CO 2 (EtCO 2) values. There were no significant differences between PCV and normoxic breathing, but PCV led to slightly higher oxygenation and carbon dioxide emission. Chowdhury et al. came to a similar conclusion after they compared the effects of different ventilations during laparoscopic cholecystectomy and found out that the PCV and its modifications demonstrated better dynamics of respiration and no significant consequences on gas exchange (5). This suggests that PCV enhances the mechanical parameter values, and both of the modes can be sufficient to maintain oxygenation with proper settings in terms of tidal volume and respiratory rate. Mechanical power is also an applicable concept in mechanical ventilation, which involves the integration of the effect of tidal volume, airway pressure and the respiratory rate to establish the amount of energy output sent to the lungs.

Rietveld et al. have demonstrated that PCV results in a reduced amount of mechanical power produced, and it reduces the chances of ventilator-induced lung injury (6). This piece of thought has special significance to patients who are undergoing extended procedures like robotic nephrectomies. According to Dhakshinamurthy and Singam, the PCV decreased dynamic airway pressure and led to enhanced patient-ventilator synchrony, which is consistent with the results that the PIP and Pplat values decreased (7). Ammar et al. studied the consequences of PCV-volume guaranteed modes in the scenario of one-lung ventilation and observed improved gas exchange and control of respiratory dynamics, which is consistent with results, albeit with different procedures (8). Furthermore, Soliman et al. concluded that PCV was favourable in obese patients who underwent laparoscopic procedures, which may be an important factor as more surgical patients are becoming obese (9). Intraoperative management is an essential part of hemodynamic stability. In that study, although heart rate did not differ between the groups, mean blood pressure (MBP) was more consistent in the PCV group, especially during pneumoperitoneum. Fuest et al. observed an equivalent hemodynamic advantage of PCV with practical applications during resuscitation attempts, where they stressed that even low orthopnoic fluctuations of intrathoracic pressure may maintain the venous circulation (10).

The prone and Trendelenburg stances are ones that pose a significant ventilatory demand. In a meta-analysis by Han et al. of patients undergoing spinal surgeries in the prone position, it was emphasised that PCV was more efficient in terms of tension in the lower airways and improved respiratory efficiency (12). This information aligns with findings in the Trendelenburg scenario. Moreover, Nasrolahzadeh et al. revealed that PCV decreased endotracheal tube cuff pressure oscillations, which helped to protect the airways during long-duration operations (13). The advantages of PCV can also be recognised in various populations of patients. Wang et al. recorded that PCV-volume involved the safest ventilation profiles in children undergoing thoracoscopic surgeries (14). Similarly, Wang et al. also found high compliance and low pressures in the airway in elderly patients treated with PCV approaches (15). These results indicate that PCV physiological benefits are universal in different age cohorts and surgical settings.

Concerning the broader implications, Hasan and Haider discovered PCV was linked to less unstable blood pressure and lesser peak pressures in laparoscopic cholecystectomies, which closely aligns with our findings (16). The results were further confirmed since Sevdi et al. determined better ventilatory performance and reduced hemodynamic variations when using PCV during bariatric surgery (17). Pournajafian et al. also showed improved respiratory variables and lowered airway pressures in laparoscopic bariatric patients by use of PCV, reinforcing the use of PCV as an ideal choice among high-risk surgical cases (18). However, the study has some limitations, even though it produced these promising results. It was carried out in a single centre, and the sample size, which is sufficient to find the differences intraoperatively, might not reflect the rare postoperative complications. Additionally, long-term post-surgery pulmonary conditions were not measured. Large multi-centre studies with prolonged follow-up sessions should be conducted to confirm the results and evaluate how the ventilatory mode can influence recovery patterns.

Conclusion

This randomised controlled investigation involved comparing the utility of pressure-controlled ventilation (PCV) and volume-controlled ventilation (VCV) in terms of their effects on respiratory mechanics and hemodynamic parameters of patients who were subjected to robotic-assisted nephrectomies. The results showed that PCV extremely decreased peak inspiratory and plateau pressures during surgery, which indicates increased levels of lung compliance and low chances of barotrauma. Also, PCV delivered more consistent mean arterial pressure in the condition of pneumoperitoneum, demonstrating better hemodynamic regulation. Although both modes have similar oxygenation and CO2 removal rates, PCV is the preferred mode of ventilation during robotic surgery, particularly in surgeries that are likely to be long and hazardous, due to its airway pressure control/cardiovascular stability. These findings are aligned with literature and conclude that PCV integration into regular anaesthetic preparations of robotic nephrectomies may provide greater operative safety and, possibly, patient outcomes. Multi-centre studies with a bigger sample and post-operative evaluation should be encouraged to confirm these results and structure any long-term respiratory and recovery advantage.

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