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Anesthesia for Robotic Surgery: Unique Challenges and Practical Solutions

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Abstract **Review Article**

Robotic-assisted surgery has significantly advanced the field of minimally invasive surgery by enhancing visualization, precision and surgeon ergonomics. These advantages have contributed to improved surgical outcomes and expanded the scope of complex procedures performed using minimally invasive techniques. However, the unique technical and positional requirements of robotic surgery pose several important anesthetic challenges that require careful anticipation and management. After docking of the robotic system, physical access to the patient becomes markedly restricted, particularly to the airway, intravenous lines, monitoring devices, and anterior torso. These limitations complicate routine adjustments and makes emergency interventions, such as airway rescue or cardiopulmonary resuscitation more difficult. Furthermore, robotic procedures often necessitate prolonged pneumoperitoneum and extreme patient positioning, most commonly steep Trendelenburg. These factors result in significant physiological alterations, including increased airway pressures, reduced pulmonary compliance, impaired gas exchange, elevated intracranial and intraocular pressures, and complex cardiovascular changes related to altered venous return and systemic vascular resistance. From an anaesthetic perspective, meticulous preoperative evaluation is essential, especially in patients with cardiorespiratory, neurological, or ophthalmic comorbidities. Intraoperatively, lung protective ventilation strategies, vigilant hemodynamic monitoring, judicious fluid management, and appropriate use of vasoactive agents are critical to maintain physiological stability. Equally important is the prevention of positioning related complications such as nerve injuries, facial and airway edema, and pressure related tissue damage.

This review highlights the key physiological implications of robotic-assisted surgery and discusses practical, evidence based anaesthetic strategies aimed at optimizing perioperative care. A structured, protocol driven anaesthetic approach is fundamental to ensuring patient safety while maximizing the clinical benefits of robotic surgical technology.

Keywords: Anaesthetic management, perioperative care, pneumoperitoneum, robotic assisted surgery, steep Trendelenburg.

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INTRODUCTION AND BACKGROUND

Robotic-assisted surgery has revolutionized the practice of minimally invasive surgery over the past two decades. Since the introduction of the da Vinci Surgical System, robotic technology has been increasingly adopted across a wide range of surgical specialties, including urology, gynecology, colorectal surgery, thoracic surgery, general surgery, and cardiac surgery. Compared with conventional open and laparoscopic approaches, robotic surgery offers several technical advantages, including three-dimensional high-definition visualization, articulated wristed instruments with seven degrees of freedom, tremor filtration, and enhanced dexterity. These innovations enable surgeons to perform highly complex procedures with greater precision while reducing blood loss, postoperative pain, length of hospital stay, and overall perioperative morbidity. Consequently, robotic-assisted surgery has become the preferred approach for many procedures such as radical prostatectomy, hysterectomy, partial nephrectomy, colorectal resections, and selected cardiothoracic operations [1, 2].

Despite these surgical advantages, robotic procedures introduce unique anesthetic challenges that differ substantially from those encountered during conventional laparoscopic surgery. Following docking of the robotic system, direct access to the patient's airway, vascular access, monitoring devices, and chest becomes markedly restricted, making even routine interventions considerably more difficult. In emergency situations such as accidental extubation, major hemorrhage, or cardiac arrest, rapid undocking of the robotic platform is essential but may delay lifesaving interventions if the operating team is inadequately prepared. The physiological consequences of robotic surgery further complicate anesthetic management. Most robotic procedures require prolonged carbon dioxide pneumoperitoneum combined with steep Trendelenburg positioning, resulting in significant alterations in cardiovascular, respiratory, neurological, renal, and ophthalmic physiology. Increased intra-abdominal pressure and cephalad displacement of the diaphragm reduce functional residual capacity, decrease pulmonary compliance, increase airway pressures, and promote ventilation-perfusion mismatch and hypercapnia. Simultaneously, elevated central venous pressure increases intracranial and intraocular pressures, while changes in preload, afterload, and systemic vascular resistance may compromise cardiovascular stability, particularly in patients with significant cardiopulmonary disease. [3-9]

Successful anesthetic management therefore requires comprehensive preoperative assessment, meticulous airway planning, individualized hemodynamic monitoring, lung-protective ventilation strategies, goal-directed fluid therapy, and close multidisciplinary communication.[9-14] Prevention of positioning-related complications, including peripheral nerve injury, facial and airway edema, pressure injuries, and rhabdomyolysis, is equally important and requires careful positioning, adequate padding, and appropriate postoperative assessment. [15-17] Recent advances in perioperative medicine, including Enhanced Recovery After Surgery (ERAS) protocols, quantitative neuromuscular monitoring with sugammadex reversal, and emerging monitoring technologies such as near-infrared spectroscopy and electrical impedance tomography, have further improved perioperative safety in robotic surgery. [10-14,18-21]

Although numerous publications have described individual physiological changes or technical aspects of robotic surgery, comprehensive reviews integrating perioperative assessment, intraoperative anesthetic management, prevention of complications, enhanced recovery principles, and emerging robotic platforms remain limited. [9-21] Therefore, this review aims to summarize the current evidence regarding the unique anesthetic challenges associated with robotic-assisted surgery and to provide practical, evidence-based recommendations for optimizing perioperative care and improving patient safety.

Review

The Robotic Operating Room Environment and Workflow

Robotic-assisted surgery has rapidly expanded across multiple specialties, with urologic and gynaecologic procedures accounting for the majority of cases (Figure 1). [1,2]

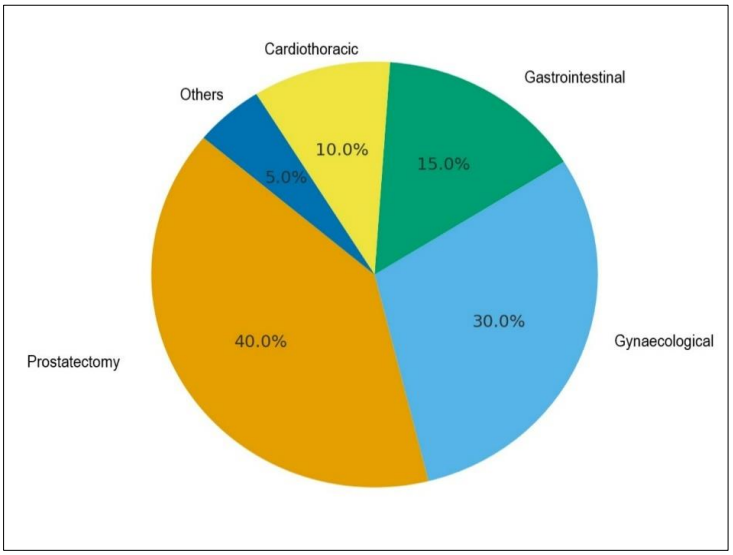


FIGURE 1: Global Distribution of Robotic Surgery Specialties

A key challenge is the altered physical environment. The robotic patient cart, with its multiple arms, is docked between the patient's legs (for pelvic surgery) or over the side of the table (for thoracic/abdominal surgery), effectively isolating the patient's upper body.

Limited Patient Access: Once docked, access to the airway, intravenous lines, and arterial lines is severely restricted. A dislodged endotracheal tube (ETT) or intravenous line can become a life-threatening emergency.

Communication Barriers: The surgeon is physically removed from the table, seated at a console, which can hinder verbal communication.

Emergency Undocking: All team members must be proficient in the rapid, safe undocking of the robot in case of a cardiac arrest or other severe physiological crisis. This requires regular, simulated drills.

Physiological Challenges and Anesthetic Management

Patient Positioning: The Steep Trendelenburg Position

For pelvic surgeries like robotic-assisted radical prostatectomy (RARP) and hysterectomy, the steep Trendelenburg position (head-down tilt of 25-45 degrees) is essential for displacing the bowel and providing a clear surgical field. This position, especially when prolonged, has significant physiological effects. [3]

Cardiovascular System: The initial head-down tilt causes an autotransfusion of blood from the lower extremities to the central circulation, increasing preload, stroke volume, and cardiac output. This can be detrimental to patients with congestive heart failure. Conversely, the increased intrathoracic pressure from pneumoperitoneum and the weight of abdominal contents on the diaphragm can compress the inferior vena cava and increase afterload, potentially decreasing cardiac output.[4]

Respiratory System: This is the most significantly affected system. The abdominal contents push cephalad against the diaphragm, leading to a marked reduction in lung compliance, functional residual capacity (FRC), and tidal volumes. This creates a significant risk for atelectasis, ventilation-perfusion (V/Q) mismatch, and hypoxemia. [5]

Neurological System: The head-down position increases central venous pressure (CVP) and jugular venous pressure, which in turn increases intracranial pressure (ICP) and intraocular pressure (IOP). This is a critical consideration for patients with glaucoma, cerebral aneurysms, or other intracranial pathology. [6]

Pneumoperitoneum: The creation of a carbon dioxide (CO2) pneumoperitoneum to facilitate surgical exposure adds another layer of physiological stress.

Cardiovascular Effects: Increased intra-abdominal pressure (IAP) compresses capacitance vessels, initially increasing venous return, but higher pressures (>15 mmHg) can compress the inferior vena cava, reducing preload and cardiac output. It also results in the production of catecholamines, which raises heart rate and systemic vascular resistance. [7]

Respiratory Effects: The elevated diaphragm reduces pulmonary compliance and increases airway pressures. The absorption of insufflated CO2 can lead to hypercapnia and respiratory acidosis, which must be countered by increasing minute ventilation. [8]

Other Effects: Pneumoperitoneum can reduce renal blood flow and glomerular filtration rate, potentially contributing to post-operative oliguria. It can also cause subcutaneous emphysema, pneumomediastinum, or pneumothorax in rare cases.

The combined effects of the Trendelenburg position and pneumoperitoneum on various organ systems are summarized in Figure 2. [3-8]

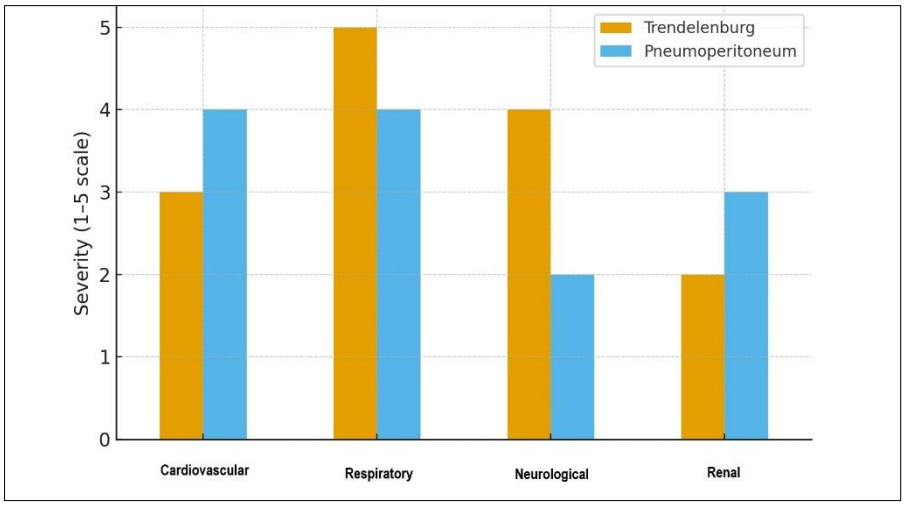


FIGURE 2: Relative Physiological Impact of Trendelenburg Position and Pneumoperitoneum

Preoperative Assessment and Planning

A thorough preoperative evaluation is crucial to determine which patients are most vulnerable to problems.

Cardiopulmonary Assessment: Particular attention should be paid to patients with poor cardiopulmonary reserve, congestive heart failure, pulmonary hypertension, or severe chronic obstructive pulmonary disease (COPD). In selected cases, preoperative echocardiography or pulmonary function tests may be warranted.

Airway Assessment: A difficult airway should be anticipated and planned for, as access after docking will be nearly impossible. A securely taped endotracheal tube is non-negotiable.

Neurological/Ophthalmic Assessment: A history of glaucoma, retinal pathology, or intracranial lesions should be documented and discussed with the surgical team to evaluate the positioning's risks and benefits.

ASA classification and use of risk tools: Use of risk tools such as STOPBANG for obstructive sleep apnea and ARISCAT score for postoperative pulmonary complications would be beneficial.

Practical Intraoperative Anesthetic Management

Monitoring

Standard Monitoring: Electrocardiogram (ECG), non-invasive blood pressure (NIBP), pulse oximetry, capnography, and temperature are mandatory.

Advanced Monitoring

Arterial Line: Strongly recommended for prolonged procedures, steep positioning, or in patients with significant comorbidities. It allows for beat-to-beat blood pressure monitoring and facilitates blood gas analysis to guide ventilation and acid-base management. [9]

Central Venous Pressure (CVP): May be considered in individuals with severe cardiac dysfunction, though its utility in the context of elevated intrathoracic pressure is debated.

Transesophageal Echocardiography (TEE): The gold standard for real-time assessment of ventricular filling and function in high-risk cardiac patients. [10]

Cerebral/Somatic Oximetry: Near-infrared spectroscopy (NIRS) can be used to monitor regional oxygen saturation, which may be compromised by positioning or hemodynamic changes, though its routine use is not yet standard. [11]

Ventilation Strategy

The combination of pneumoperitoneum and Trendelenburg position creates a scenario ripe for ventilator induced lung injury (VILI). A lung-protective ventilation strategy is essential. [12]

Low Tidal Volumes: Use 6-8 mL/kg of predicted body weight to reduce volutrauma and barotrauma.

Application of PEEP: Positive end-expiratory pressure of 5-10 cm H_2O is critical to prevent cyclic alveolar collapse and maintain FRC.

Recruitment Maneuvers: Periodic alveolar recruitment maneuvers (e.g., applying 30-40 cm $H_2O$for 30-40 seconds) can be performed after docking, during position changes, and before undocking to re-expand atelectatic lung areas. [13]

Permissive Hypercapnia: Mild hypercapnia ($PaCO_2$> 50-60 mmHg) may be acceptable if the pH remains >7.25, to avoid dangerously high airway pressures. However, significant respiratory acidosis should be corrected.

Intraoperative carbon dioxide (CO2) monitoring: Pneumoperitoneum can increase PaCO2 by 10-15 mmHg, making continuous CO2 monitoring essential. Intervene if EtCO2 rises more than 40-50 mmHg despite increased minute ventilation or if ABG shows PaCO2 more than 60 mmHg or pH less than 7.2. To limit CO2 absorption, keep intra-abdominal pressure less than 12-15 mmHg.

Hemodynamic and Fluid Management

Goal-directed fluid therapy (GDFT) is the paradigm of choice. Overzealous fluid administration can exacerbate facial and airway edema, while under resuscitation can lead to acute kidney injury. [14]

Crystalloid Restriction: A conservative approach with 1-3 mL/kg/hr of balanced crystalloid is often sufficient.

Use of Dynamic Parameters: Stroke volume variation (SVV) or pulse pressure variation (PPV) from an arterial line can guide fluid boluses more accurately than static measures like CVP.

Vasopressor Support: The use of vasopressors like phenylephrine or norepinephrine is common to counteract the vasodilation from anesthetics and the increased afterload from pneumoperitoneum, allowing for a more restrictive fluid strategy.

Prevention and Management of Position Related Complications

Airway Edema: Prolonged head-down position can cause significant edema of the face, neck, pharynx, and larynx. This poses a critical risk for post extubation upper airway obstruction. [15]

Solution: A leak test around the endotracheal tube should be performed after returning the patient to the supine position and before extubation. One must have a low threshold for delayed extubation or overnight intubation in long procedures (>5-6 hours), in fluid-overloaded patients, or if there is any concern about airway edema.

Neurological Injuries:

Brachial Plexus Injury: The most common nerve injury, caused by excessive shoulder brace pressure or arm abduction >90 degrees. [16]

Solution: Use padded sled-style braces placed on the acromioclavicular joint, not in the axilla. Arms should be tucked at the side in a neutral position ("military position") with adequate padding.

Other Nerves: Common peroneal, sciatic, and ulnar nerves are also at risk and require meticulous padding.

Pressure Sores and Rhabdomyolysis: The extreme positioning concentrates pressure on small body areas. Rhabdomyolysis of the gluteal muscles or lower extremities is a rare but serious complication, particularly in muscular males with a high body mass index (BMI) and prolonged operative times. [17] BMI more than 30 increases the risk of airway edema, rhabdomyolysis risk and BMI more than 40 (morbid obesity) decreases functional residual capacity (FRC) by upto 20-25% under pneumoperitoneum.

Solution: Meticulous padding of all pressure points (head, shoulders, elbows, sacrum, heels). Limiting operative time and maintaining a high index of suspicion with post-operative creatine kinase (CK) monitoring in high-risk cases.

Enhanced Recovery After Surgery (ERAS) protocol for surgery

ERAS principles play a crucial role in optimizing outcomes in robotic procedures. Carbohydrate loading with clear carbohydrate-rich drinks up to two hours before anesthesia reduces perioperative insulin resistance and improves patient comfort without increasing aspiration risk. Early ambulation is strongly emphasized to counteract venous stasis from pneumoperitoneum and Trendelenburg positioning, reducing the risk of atelectasis, ileus, and thromboembolism. ERAS also prioritizes opioid-sparing multimodal analgesia (paracetamol, NSAIDs, regional blocks, low-dose ketamine, lidocaine infusion) to facilitate faster recovery and decrease postoperative nausea, sedation, and delayed mobilization. Careful goal-directed therapy helps avoid fluid overload, as excessive intravascular volume worsens airway edema after steep Trendelenburg and increases postoperative respiratory complications. Finally, extubation criteria after extreme Trendelenburg require confirmation that airway edema has resolved assessed via cuff-leak test, absence of facial/oropharyngeal swelling, adequate spontaneous ventilation, normocapnia, and full neuromuscular reversal before attempting awake extubation. Figure 3 illustrates the common anaesthetic complications during robotic surgery. [15-17]

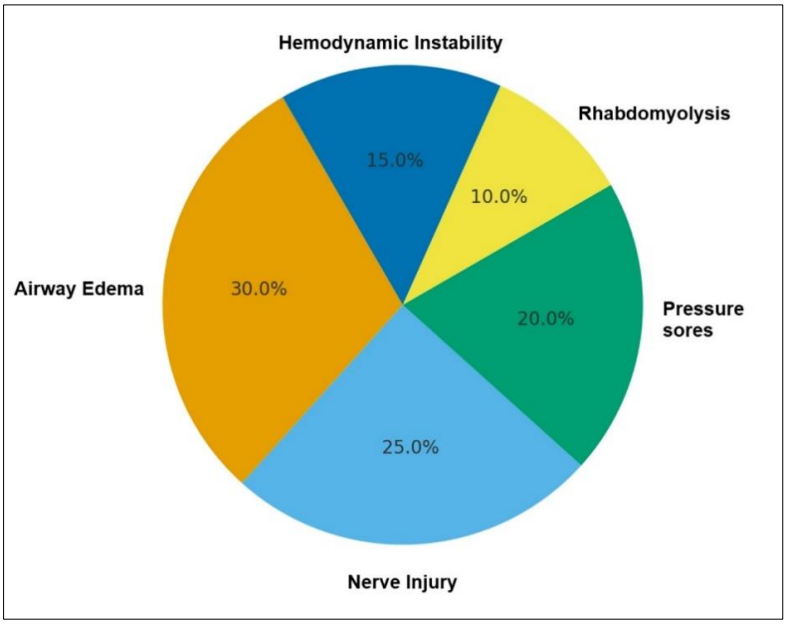


FIGURE 3: Common Anaesthetic Complications During Robotic Surgery

Robot platforms

The da Vinci Surgical System (Intuitive Surgical) is the most widely used robotic platform worldwide. It features a fixed patient cart with three to four robotic arms and a surgeon console providing 3D, high- definition visualization and wristed instruments

with seven degrees of freedom. For anesthesiologists, the da Vinci platform typically requires a steep Trendelenburg position, tight arm docking around the patient, and restricted access to the airway and chest once the robot is engaged.

Newer systems provide design alternatives with different ergonomic and anesthetic considerations. The Hugo RAS system (Medtronic) uses modular, independent robotic arms mounted on movable carts, allowing flexible OR configuration but proper planning is needed to prevent clutter, ensure safe cable routing, and maintain a clear path for airway access during emergencies. The Versius system (CMR Surgical) employs small, lightweight bedside units with individually positioned arms, designed to reduce OR footprint and improve maneuverability; however, distributed arm placement can limit rapid patient access if not arranged thoughtfully. Although all platforms require similar insufflation and patient positioning for pelvic surgery, differences in arm geometry, spacing, and docking strategies influence anesthetic access, monitoring lines, and emergency undocking logistics.

Emerging Concepts and Future Directions

Research continues to refine best practices. The role of sugammadex for ensuring complete reversal of neuromuscular blockade is paramount to prevent post-operative pulmonary complications. [18] The use of dexmedetomidine as an adjunct has shown benefits in attenuating the hemodynamic response to pneumoperitoneum and providing analgesia while reducing opioid consumption. [19] Furthermore, the integration of advanced monitoring like electrical impedance tomography (EIT) to visualize regional lung ventilation in real-time may further optimize ventilation strategies in the future. [20]

Level of Evidence

The strongest available evidence supporting anesthetic management in robotic surgery pertains to lung-protective ventilation strategies and goal-directed fluid therapy, whereas recommendations for several other perioperative practices are primarily based on observational studies and expert consensus. [21,22] Lung-protective ventilation during pneumoperitoneum is supported by Level I evidence, including randomized controlled trials and meta-analyses, demonstrating improved pulmonary outcomes and reduced postoperative complications.[12,13] Similarly, goal-directed fluid therapy is supported by Level I–II evidence, with studies showing improved hemodynamic stability and reduced perioperative morbidity. [14,21] The use of a cuff-leak test before extubation to identify clinically significant airway edema is supported by Level II–III evidence. [15] Near-infrared spectroscopy (NIRS) for cerebral oxygenation monitoring is supported by Level II evidence, although its routine use remains limited to selected high-risk patients. [11] In contrast, recommendations regarding emergency robotic undocking drills are largely based on Level III evidence and expert consensus, emphasizing the importance of multidisciplinary simulation training to ensure rapid and coordinated responses during intraoperative emergencies. [9,22]

CONCLUSIONS

Anesthesia for robotic surgery demands a proactive, physiology-based approach. The anesthesiologist must be an expert in managing the profound cardiopulmonary consequences of pneumoperitoneum and extreme patient positioning. Success hinges on meticulous preoperative planning, vigilant intraoperative monitoring with a low threshold for invasive techniques, and the disciplined application of protective ventilation and fluid strategies. A well-rehearsed team protocol for emergencies, including rapid undocking, is the final critical component. By mastering these challenges, the anesthesiologist ensures that the significant benefits of robotic surgery are not overshadowed by preventable anesthetic morbidity. The future of robotic anesthesia will incorporate AI-driven physiologic monitoring, automated ventilator adjustment systems, greater integration with single-port robotic platforms. Mastery of physiologic principles combined with emerging technologies will further enhance patient safety and outcomes in the robotic operating suite.

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