Anesthesia of robotic thoracic surgery

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Submitted Jan 18, 2015. Accepted for publication Mar 01, 2015.
doi: 10.3978/j.issn.2305-5839.2015.03.03
View this article at: http://dx.doi.org/10.3978/j.issn.2305-5839.2015.03.03

Introduction

Robot-assisted thoracic surgery is one of the more mature techniques among minimally invasive surgeries. With the improvement of the cooperation between operative and surgical proficiency, the operation and perioperative times required for each stage of robot-assisted thoracic surgery have been gradually shortened. The advantages of robot-assisted thoracic surgery are also increasingly prominent.

The bulkiness and particularity of the robot operating technology render anesthetic management both difficult and complex. In addition, the anesthesia requirements of thoracic surgery are different from those of robot-assisted surgeries of other specialties. In particular, CO_2, artificial pneumothorax, prolonged one-lung ventilation (OLV) and other factors exert significant influence on respiration and circulation, making anesthesia in thoracic surgery a more demanding procedure. The anesthesiologist must fully understand not only the surgical technique and the related equipment but also their impacts on the patient and the corresponding pathophysiological changes to ensure both the success of the surgery and patient safety.

Pre-anesthetic visit and assessment

Robot-assisted thoracic surgery usually involves multiple small incisions and applies artificial tension pneumothorax and prolonged OLV; thus, patient selection is strict. This precaution is directly related to the occurrence of perioperative complications and the overall therapeutic effect.

In addition to the preoperative routine examination performed for thoracic laparoscopic surgery, assessment of the intubation conditions needs to be emphasized. If it is likely going to be difficult for the patient to be intubated (e.g., the patient has severe trismus, severe facial deformities or severe scoliosis), the patient should be classified as having an anesthesia contraindication. Although pulmonary function measurements are not necessarily related to postoperative ventilatory failure, nor are they necessarily predictive for the occurrence of postoperative respiratory failure, pulmonary function testing, blood gas analysis and chest X-ray can all help determine whether a patient can tolerate the prolonged OLV. Under the resting state air inhalation conditions, if conditions such as hypercapnia ($PaCO_2$ >50 mmHg), hypoxemia (PaO_2 <65 mmHg), chronic obstructive pulmonary disease (COPD), bronchospasm, asthma, or severe emphysema are detected, then the patient cannot tolerate OLV and the hypercapnia, hypoxemia and pleural positive impact caused by continuous CO_2 infusion. Therefore, these patients are not suitable for this type of surgery. Patients with moderate COPD should go through hormone and physical therapy with bronchodilators or adrenocorticotropic steroids and wait until their lung functions are improved before being considered for robot-assisted thoracic surgery. Those patients who have long smoking histories must quit smoking 1 to 2 weeks prior to the surgery. Obese patients usually have reduced tolerance to OLV and are encouraged to try to lose weight before the surgery. Very young patients are also not suitable for robot-assisted thoracic surgery due to their small body size and short height, which make them unfit for OLV.

Secondly, the evaluation of the patient's cardiopulmonary function should be conducted according to the clinical guidelines for non-cardiac surgery within the chest. Those patients who are suffering from unstable angina or a recent myocardial infarction are particularly sensitive to acute myocardial ischemia and trauma during the surgery and are more vulnerable to heart failure. Therefore, precautions must be exercised when selecting these patients for robot-assisted thoracic surgery. All of a cardiac patient's cardiovascular medications must be continued until the day of surgery, especially β-blockers, which should be continuously applied to reduce the stress on the myocardium and to maintain a relatively slow heart rate. However, for elderly patients who are unusually sensitive to β-blockers, greater caution should be exercised; in particular, in case of the application of intraoperative and postoperative thoracic epidural blocks, sympathetic nerves will be further blocked, and some patients might not be able to tolerate the procedure. In case of electrolyte abnormalities, especially arrhythmias caused by potassium and magnesium abnormalities, the electrolytes need to be controlled within the normal range before the surgery.

In addition, the patient's coagulation parameters should be within the normal range, and patients' medications on aspirin and other antiplatelet drugs need to be discontinued at least 7 days before the surgery. Oral anticoagulants (dicoumarol) also need to be discontinued for a sufficient time prior to the surgery.

Indications and contraindications of anesthesia

Indications

(I) Clear surgical indications, such as lobectomy and lymph node dissection, esophageal surgery, and less than 5 cm mediastinal neoplasm resection, are all indications for robot-assisted thoracic surgery;
(II) The patient's condition: the body height should be greater than 130 cm, and the body weight should be more than 30 kg;
(III) Respiratory system conditions: examinations of lung function, blood gas analysis, chest X-ray and airway should be normal and viable for double-lumen endotracheal intubation and should be tolerant to OLV;
(IV) Cardiovascular system conditions: no acute coronary syndrome, heart failure, serious arrhythmias or severe valvular disease should be present;
(V) Laboratory tests: no liver or kidney dysfunctions and coagulation disorders should be present;
(VI) Others: the patient should meet the requirements for conventional thoracotomy or thoracoscopic surgery.

Contraindications

(I) Patients who have severe airway difficulties and severe thoracic or spinal deformities in the preoperative assessment should not be considered;
(II) Patients who are suffering from severe COPD, severe pulmonary hypertension, severe emphysema, bronchial asthma, and severe pleurisy or ipsilateral pleural adhesions should not be eligible;
(III) Patients who have a history of cardiac surgery or chest surgery should not be considered;
(IV) Other special cases that are unfit for thoracic surgery and anesthesia should not be considered.

Anesthesia method

Intraoperative monitoring

Robot-assisted thoracic surgery anesthesia does not require special procedures besides the clinical anesthesia monitoring requirements proposed by the American Society of Anesthesiologists (ASA). Some complex non-invasive or invasive monitoring techniques can be selected according to the actual condition of the patient. In developing a perioperative care strategy, anesthesiologists must take full account of factors such as the surgeon's surgical experience and the possible operation time, along with the risks introduced by changes in these factors.

Routine monitoring indicators should include 5-lead electrocardiogram (ECG), pulse oximetry, end-tidal carbon dioxide ($P_{ET}CO_2$), continuous invasive arterial pressure, central venous pressure, bispectral index, degree of neuromuscular blockade, temperature monitoring, and others.

Surgical incisions in the left side of the chest might affect ECG monitoring to some extent. In particular, such incisions render the V4~V6 leads, which are more sensitive in the diagnosis of myocardial ischemia in the frontal lateral wall, unusable. Artificial pneumothorax can change the axis and amplitude of the ECG and can further impact the judgment of myocardial ischemia and arrhythmia. Therefore, it is necessary to simultaneously monitor changes in leads II and changes in the lateral chest lead ECG and the ST segment.

$P_{ET}CO_2$ mainly reflects on the ventilation conditions, rather than directly on the body's acid-base status and oxygenation, especially in the case of robot-assisted thoracic surgery, which is under comprehensive influences by many factors. $P_{ET}CO_2$ measurements can vary significantly at different times; however, most of the time, there is a good correlation between $P_{ET}CO_2$ and $PaCO_2$, and observation of the dynamic change of $P_{ET}CO_2$ is useful in the judgment of $PaCO_2$. Therefore, $P_{ET}CO_2$ can be routinely used for robot-assisted thoracic surgery but cannot completely replace blood gas analysis. In particular, in cases of OLV and prolonged OLV-induced composite carbon dioxide pneumothorax, the blood gas analysis should be conducted regularly to make timely adjustments.

Transesophageal echocardiography (TEE) is used for robot-assisted thoracic surgery monitoring only in very special circumstances. If the patient has severe cardiovascular dysfunction, TEE in robot-assisted thoracic surgery can provide references for the anesthesiologist in regard to double-lumen endotracheal tube positioning, the dynamic monitoring of left ventricular myocardial ischemia and cardiac function, guiding the capacity treatment, and other procedures.

Selection of anesthesia

General anesthesia

Relative to laparoscopic surgery, robot-assisted surgery requires more complete muscle relaxation. After the operation arm is mounted with the instrument and enters the patient's body, the patient's position cannot be changed. Patient body movement during the surgery may lead to serious consequences; thus, it is especially important to have perfect neuromuscular monitoring and muscle relaxant application. During the induction and maintenance of anesthesia, intravenous or inhaled anesthetics that have relatively small hemodynamic impacts are preferred. Halide inhalation anesthetics have strong anesthetic effects and low minimum alveolar gas effective concentrations, which can be coupled with high oxygen concentrations. In addition, halide inhalation anesthetics lead to rather low blood/air partition coefficients and can also speed the induction of anesthesia and awakening, which are easier to control and therefore especially suitable for thoracic anesthesia.

Combined regional anesthesia with general anesthesia

It has been reported that combined regional anesthesia with general anesthesia can be applied to robot-assisted thoracic surgery anesthesia. The advantages of this method are that it can reduce the amount of anesthetics needed for general anesthesia during the intraoperative maintenance period and can have a smaller hemodynamic impact, with a smooth transition to postoperative analgesia. In general, fast and lightly induced anesthesia is combined with a thoracic paravertebral block. First, a paraspinal block is performed; when successful, general anesthesia is induced using fentanyl (3-5 μg/kg), propofol (0.5-1 mg/kg), and rocuronium (1 mg/kg). In the intraoperative duration, low-dose propofol (50 μg/kg/min) is continuously and intravenously applied, together with a single dose of an intravenous injection of rocuronium to maintain anesthesia. However, this method is time-consuming, and the paravertebral block also has a certain failure rate.

Pre-anesthesia medication

Currently, pre-surgical medication is generally not applied. When the patient is wheeled into the surgery room, midazolam 2 mg and/or penehyclidine 0.5-1 mg are intravenously injected into the patient to help reduce airway secretions and to prevent laryngeal spasm during the intubation. Intravenous injection of dexmedetomidine (1 μg/kg, 10-15 min) before the induction can generate a good sedative effect and a stable hemodynamic effect, which is a viable option.

Induction of anesthesia

The induction of anesthesia is usually performed by intravenous induction. The optional intravenous anesthetics include propofol (1.5-2.5 mg/kg) or etomidate (0.3 mg/kg), while the narcotic analgesics include the most commonly used sufentanil (0.5-1 μg/kg). The muscle relaxants have a very wide range of choices, among which rocuronium (0.6-0.9 mg/kg) is most commonly used. Other drugs can be used appropriately based on the patient's condition. After successful muscle relaxation, double-lumen endotracheal intubation is performed, and mechanical ventilation is executed after the bronchoscopy positioning.

Maintenance of anesthesia

Anesthesia can be maintained by continuous intravenous infusion of propofol (4-6 mg/kg/h) and remifentanil (0.3-0.5 μg/kg/min), and alternatively by targeted, controlled infusion of propofol with a final plasma concentration of 1-1.5 μg/mL and remifentanil with a final plasma concentration of 5-10 ng/mL. The patient's response to surgical stress and sedation can be determined based on hemodynamic changes and the bispectral index (BIS), while the anesthetic depth can be controlled by adjusting the concentration of sevoflurane inhalation. Muscle relaxants can be injected intermittently and intravenously according to the requirements of muscle relaxation. Thirty minutes before the expected completion of surgery, inhalation of anesthetics is discontinued, and the intravenous anesthetic propofol and narcotic analgesic remifentanil infusion rates are gradually increased as guided by the hemodynamic parameters to maintain the proper depth of anesthesia. Meanwhile, a single intravenous injection of sufentanil (5-15 μg) or a non-steroidal anti-inflammatory analgesic can be performed. At the end of the surgery, intravenous infusions of anesthetics and narcotic analgesics are stopped. Because this anesthesia method adopts intravenous infusion or injection of the drugs at the induction and awakening stages while adopting a combined intravenous and inhalational application of the drugs in the maintenance stage, it is also called "the sandwich technique”. This anesthesia technique can ensure early extubation and rapid patient recovery.

Robot-assisted thoracic surgery anesthesia should appropriately limit the uses of opioids, benzodiazepines and muscle relaxants. Generally, the inhaled concentration of sevoflurane is 3-5%. The application of midazolam to maintain anesthesia intraoperatively is not recommended to facilitate early postoperative extubation. Remifentanil can provide hemodynamic stability and has a better inhibitory effect on the stress response than the traditionally used opioids. In addition, remifentanil has no delay of postoperative respiratory depression and no need of prolonged postoperative ventilator support and, thus, is more reasonable for use in maintaining anesthesia in robot-assisted thoracic surgery than fentanyl or sufentanil.

Anesthetic management

Robot-assisted thoracic surgery is a new challenge to surgeons and anesthesiologists. The surgeon has to complete various surgical procedures in a small space, which requires high stability of the respiratory cycle and demands regular communication and cooperation between the anesthesiologist and the surgeon. The anesthesiologist needs to be vigilant and to pay special attention to the impacts of prolonged operation on the circulation, oxygen deficiency derived from the OLV, hyperintrathoracic pressure caused by CO_2 pneumothorax and the surgical procedure and should actively respond should these abnormalities occur. The focus of anesthesia management is to maintain the respiratory function and hemodynamic stability.

Issues related to anesthesia management

The bulky robot requires a large space in the surgery room, which inevitably distances the anesthesiologist and the patient. With the robot, monitors, displays surrounding the patient, the anesthesiologist often does not have easy access to the patient during the surgery. To facilitate the surgical exposure and the surgeon’s work, the patient is placed at a 90° angle to the anesthesiologist, in which the patient’s head and arms are all blocked by the robot. When the robot assumes its position and is secured, it may be the case that the anesthesiologist is not able to complete the necessary close operations, thus increasing the risk in the surgery. Therefore, all narcotic operations, including the establishment of the central venous channels, invasive arterial pressure catheterization and the confirmation of lung isolation, etc., have to be completed before the patient’s final position is secured.

To ensure smooth intraoperative management, long infusion pipelines are used, and the positions of three-way valves and injections are reasonably set so that they can be adjusted under direct vision. Similarly, the cords to the monitors and the ventilator circuit should also be long enough for the anesthesiologist to work remotely and should be fastened in the cluster and in a visible manner to avoid any disconnections caused by the movement of the surgical bed. Because the patient’s head position is blocked by the main body of the robot, anesthesia headstock cannot be used; in addition, the use of prolonged threaded pipe also increases the risk of disconnection of the endotracheal catheters. Therefore, the endotracheal catheters and the ventilator circuit must be well connected to each other and securely fastened. A dedicated pipeline holder for anesthesia tubes can be used as long as they do not affect the robot arm.

During the surgery, the robot’s position cannot change in relation to the patient’s movement. Because any movement of the patient’s chest will lead to accidental organ damage or vascular cutting, with serious consequences, adequate muscle relaxation and absolute braking on the patient must be ensured. Appropriate muscle relaxants need to be administered to patients, even those with myasthenia gravis. Although neuromuscular monitoring has some significance, there are still some problems to be solved regarding its implementation process. There are various factors in robot-assisted thoracoscopic surgical procedures that can cause pressure on the patient’s body, which can lead to severe nerve damage on the pressured area (such as the commonly occurring brachial plexus injury). In addition, special attention should be paid to protection of the facial skin and eyes; foam pad protectors can be used when necessary to prevent bruises to the face and eye damage. For patients suffering from spine diseases, especially when combined radicular symptoms or corresponding impaired nerve function, special care must be taken to minimize the risk of orthostatic nerve/muscle complications during lateral position surgery.

Management of OLV

In robot-assisted thoracic surgery, anesthetic techniques of lung isolation and OLV are essential, of which the most commonly used methods include double-lumen endotracheal intubation or single-lumen tube with bronchial occlusive cuff (e.g., a Univent catheter). For patients with difficult-to-plant intubation, bronchial occlusive catheters are preferred over double-lumen tubes. If double-lumen tubes are used, the appropriate intubation model (currently the most widely used ones are left lateral surgical double-lumen endotracheal catheters) should be selected while taking into account the patient's gender, height, weight and other comprehensive factors. Under the condition of no airway injury, larger-sized catheters are preferred. During the intubation process, the use of bronchoscopy is helpful to determine the catheter position and to assess airway anatomical abnormalities or airway foreign bodies. Lung isolation must be confirmed before performing OLV.

During OLV, the respiratory rate and tidal volume are first adjusted. While maintaining hemodynamic stability and not affecting the surgery, adequate minute ventilation should be ensured as much as possible and the tidal volume setting should not be too high so that the airway pressure can be maintained at 20-30 mmHg. If intraoperative lung inflation is necessary, special care has to be taken to avoid the iatrogenic spread of tumor tissue into the lung parenchyma by the intrathoracic surgical instruments.

One of the problems of prolonged OLV is that the ipsilateral lung is under a non-ventilated condition, which readily leads to CO_2 accumulation; secondly, the lateral atelectasis can lead to increased pulmonary artery pressure, pulmonary vascular resistance and right ventricular filling pressure, with reduced intrathoracic blood flow and reduced cardiac output, eventually leading to hypoxemia and hypercapnia, especially among obese patients and/or long-term smokers. In addition, OLV can cause atelectasis, pulmonary edema and ventilation/perfusion disorders. The adverse effects caused by OLV can even be extended to the postoperative stage, directly impacting on the patient's recovery and prognosis. A continuous positive airway pressure (CPAP) (5-10 cmH_2O) exerted on the ipsilateral lung helps to improve oxygenation and reduce diversion. The intraoperative application of double-lumen tubes is meant to make the ipsilateral lung collapse; additionally, low tidal volume ventilation or positive end-expiratory pressure (PEEP) is sometimes needed on the contralateral lung, which might increase the central venous pressure, pulmonary artery pressure, and intrathoracic pressure and might therefore enhance the CO_2 level or even cause hypoxic vasoconstriction.

Measures to address OLV-related problems include close monitoring of SpO_2, $P_{ET}CO_2$ and real-time monitoring of arterial blood gases. Once hypoxemia or CO_2 accumulation occurs, the respiratory parameters should be actively adjusted, and the respiratory rate is usually adjusted to a level 20% higher than that for double-lung ventilation. If SpO_2 continuously decreases, the surgeon should be notified to suspend the surgery; double-lung ventilation then needs to be applied to correct hypoxia and to resume the OLV and the surgery.

Management of CO_2 pneumothorax

Robot-assisted thoracic surgery requires not only OLV but also continuous blowing of CO_2 into the ipsilateral chest, producing an artificial pneumothorax to exclude air, to increase protection from electrical burns and to reduce the incidence of air embolism while facilitating lung collapse, revealing the surgical field. The pressure of the artificial pneumothorax is usually 5-12 mmHg, which may cause increased CO_2 levels in the blood; coupled with the *in vivo* accumulation of CO_2 resulting from OLV, CO_2 pneumothorax may have a significant impact on a severely ill patient. If the pressure of the blowing CO_2 cannot be strictly controlled and monitored, the artificial pneumothorax may sometimes lead to tension pneumothorax, giving rise to significantly decreased venous return and hypotension. The risks of CO_2 pneumothorax also include venous air embolism, reduced blood amount in right side of the heart and acute cardiovascular collapse (i.e., hypotension, hypoxemia, arrhythmia, etc.), even causing a positional change of the double-lumen balloon.

During the surgery, the air blowing pressure, airway pressure, exhaled tidal volume and central venous pressure should be monitored in real time. Central venous pressure monitoring helps to assess the impact of artificial CO_2 pneumothorax, while direct monitoring of the pleural cavity pressure can avoid excessive pressure-induced tension pneumothorax. To minimize the impact of CO_2 pneumothorax, it is recommended that CO_2 be slowly applied one minute after the opening of the chest, and its blowing speed should be adjusted according to hemodynamic changes. Appropriate reducing CO_2 blowing pressure also alleviates the impact of pneumothorax.

Intraoperative circulation management

Through pulmonary artery catheterization, chest bioelectrical impedance, TEE and other technologies, it has been demonstrated that CO_2 pneumothorax can reduce cardiac output by 10% to 30%. Measurements of venous oxygen saturation and lactate concentrations have demonstrated that patients are generally well tolerant of hemodynamic changes during CO_2 pneumothorax. The reduced cardiac output is associated with various factors, such as increased vena cava pressure induced by the increased intrathoracic pressure, increased venous resistance, retention in the venous blood, and others. The reduction in reflux is proportional to the decrease of the cardiac output. OLV induces lung V/Q imbalance, increases pulmonary artery pressure and reduces cardiac output; CO_2 pneumothorax elevates mediastinal pressure, inhibits systolic and diastolic functions and accelerates the accumulation of CO_2 in the body, leading to acidosis, which is manifested by decreased blood pressure and high heart rate. The blood pressure can be raised by rapid fluid replacement and vasopressor application via appropriate uses of phenylephrine or dopamine. Some believe that appropriately controlling the infusion amount can reduce exudate in the surgical field and can make it easier to operate; in the absence of massive bleeding, infusion of excessive liquid is indeed unnecessary.

Management of fluid balance and body temperature

Fluid balance is essential. Adequate intravascular volume is the prerequisite to hemodynamic stability and adequate organ perfusion. Robot-assisted thoracic surgery usually adopts limited fluid treatment strategies to ensure the patient's central venous pressure is slightly lower than its preoperative level.

In prolonged robot-assisted thoracic surgery, the body temperature must be closely monitored to avoid the adverse effects caused by intraoperative hypothermia. The nasopharyngeal temperature should also be routinely monitored. Generally, the patient's body temperature should be appropriately maintained above 36 ℃. To prevent hypothermia, a proper operating room temperature should be maintained, and the exposure time of the patient should be minimized when positioning the patient's body; insulation can be used if necessary.

Management of intraoperative internal environment

CO_2 pneumothorax during robot-assisted thoracic surgery can cause increased CO_2 levels in the blood while OLV can also cause the *in vivo* accumulation of CO_2. The reduced cardiac output and elevated mediastinal pressure induced by OLV and CO_2 pneumothorax can accelerate *in vivo* CO_2 accumulation. The necessity of intervention to adjust the body's acid-base balance depends on the decompensation between arterial blood gas pH and base excess; if the patient has poor cardiopulmonary function and loses self-regulation of the acid-base balance during prolonged surgery and shows respiratory acidosis complicated by metabolic acidosis decompensation, correction is necessary, and special attention should be paid to the occurrence of metabolic acidosis decompensation coupled with hyperkalemia.

Emergency responses

Starting from preoperative preparation, the anesthesiologist and the entire surgical team must always be prepared for the emergency of converting the procedure to an open surgery, which is different from traditional thoracoscopic surgery. Whether it is lung, esophageal or mediastinal robot-assisted thoracic surgery, sudden, excessive and difficult-to-control thoracic bleeding is the most serious complication in robot-assisted thoracic surgery, and the consequences could be disastrous. An emergency plan to be implemented in response to major blood loss and cardiovascular accidents must be developed. In robot-assisted thoracic surgery, unlocking and removing the robot is the first step to be taken under a state of emergency. Each member of the team should be familiar with this operation, ensuring that the robot can be unlocked and removed within 1 minute in case of a crisis. At the same time, the entire team should have acquired the basic skills of CPR training and knowledge of advanced life support. Of particular note, before the artificial pneumothorax is removed and double-lung ventilation is restored, successful external defibrillation can be very difficult; therefore, external defibrillation should not be performed before unlocking and removing the robot.

Postoperative analgesia

Compared with pain in conventional thoracic surgery, pain after the robot-assisted thoracic surgery is present to a lesser extent; nonetheless, some degree of pain stress is still present and can be detrimental to the patient's postoperative rehabilitation. Typically, significant postoperative pain continues for approximately 48 h. Analgesic options include continuously applied wound infiltration anesthesia through a porous catheter, intercostal nerve block, paravertebral block, pleural cavity analgesia, epidural block, intrathecal morphine injection, and patient-controlled intravenous analgesia (PCIA), among others. All of these options provide high-quality analgesic efficacy. Paravertebral block combined general anesthesia is an important method of intraoperative and postoperative analgesia and also serves as one of the multimodal analgesia regiments. Continuous percutaneous paravertebral block can provide safe and effective postoperative analgesia. Intrathecal anesthesia is also used for postoperative analgesia with satisfactory analgesia. PCIA is currently the most commonly used clinical postoperative analgesia and has satisfactory analgesic effects.

Cite this article as: Zhang Y, Wang S, Sun Y. Anesthesia of robotic thoracic surgery. Ann Transl Med 2015;3(5):71. doi: 10.3978/j.issn.2305-5839.2015.03.03

Acknowledgements

Disclosure: The authors declare no conflict of interest.

