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Case Report

Anesthesia management for total robotic liver transplantation: Inaugural case series in Europe

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Robotic liver transplantation represents a cutting-edge technique that may surpass traditional open surgery. Nonetheless, it introduces unique anesthetic challenges, including extended pneumoperitoneum, restricted patient access, and a risk of undetected blood loss. This article describes an anesthetic approach and patient outcomes for the first four total robotic liver transplants performed at a tertiary university hospital in Portugal, along with inaugural procedures of their kind in Europe. We retrospectively analyzed surgical and anesthetic data from four patients who underwent total robotic liver transplantation from February to April 2024. Data encompassed clinical profile, preoperative assessment, surgical and anesthesia details, postoperative course, and outcomes. Patients' age ranged from 51 to 69 years. Their cirrhosis was primarily due to alcohol use, hepatitis C virus infection, hepatocellular carcinoma, or nonalcoholic steatohepatitis. General anesthesia was administered. Hemodynamic monitoring and goal-directed fluid therapy were conducted using a PiCCO system. Blood loss varied from 1,000 to 5,000 mL. Blood products were transfused as needed. All donor livers underwent hypothermic oxygenated machine perfusion before transplantation. After surgery, two patients were immediately extubated, while two required extended ventilation. Hospital stays ranged from 10 to 40 days. The 30-day survival rate was 100%. This initial case series affirmed the feasibility and safety of total robotic liver transplantation for carefully selected patients, yielding favorable short-term results. Anesthetic management can rely on proactive strategies, acute situational awareness, and effective multidisciplinary collaboration.

Key Words: Liver transplantation; Minimally invasive surgical procedures; Robotic surgical procedures; Transplantation

INTRODUCTION

Orthotopic liver transplantation serves as a therapeutic gateway for acute or chronic end-stage liver disease of any etiology. Traditionally, surgeons have performed this procedure via laparotomy. However, minimally invasive surgery has recently sparked increasing interest across various surgical fields, aiming to improve clinical outcomes by decreasing blood loss, reducing complication risks, alleviating postoperative pain, enabling faster recovery, and shortening hospital stays [1].

Robotic surgery offers enhanced precision and visualization, including three-dimensional high-definition imaging, elimination of hand tremors, and an expanded range of motion. It has been proven to be particularly beneficial for complex surgeries involving multiple vascular anastomoses [1-3]. In recent years, robotic surgery has emerged as an alternative to laparoscopic surgery for various liver procedures, potentially offering significant benefits [4]. A meta-analysis comparing robotic versus open hepatectomies has indicated that the robotic approach can yield better outcomes, although it typically involves longer operating time [3].

Nonetheless, the experience with robotic liver transplanta-

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tion surgery remains limited. Although deceased donor liver transplants (DDLTs) have historically been conducted through laparotomy and a whole liver transplant, robotic assistance has been successfully employed for partial donor hepatectomies in living donor liver transplant (LDLT) procedures. This occurred after robotic assistance was being performed as an alternative to a non-transplant related hepatic surgery [2]. Although LDLT partial liver donor hepatectomies were increasingly performed in different centers with success [4,5], the first-ever liver transplant using whole liver DDLT occurred at Saint Louis Hospital in the United States in 2023 [6].

To the best of our knowledge, only nine such transplants have been performed worldwide up to date. This article reports four of those cases, including the first total robotic liver transplant performed in Europe at the Hepato-Biliary-Pancreatic and Transplantation Centre of Hospital Curry Cabral, Local Health Unit of São José, a leading tertiary university hospital and main liver transplant center in Portugal.

Our aim was to outline an anesthetic approach employed in this patient series, examine potential intraoperative and postoperative complications, and consider approaches that might further enhance patient care in this challenging field.

CASES

We conducted a retrospective analysis of patients who underwent a total robotic liver transplant at the Hepato-Biliary-Pancreatic and Transplantation Centre of Hospital Curry Cabral,

Table 1. Summary of patient demographics, operative and anesthesia details, complications, and outcomes

Patient	Case 1	Case 2	Case 3	Case 4
Age (yr)	51	66	69	60
Sex	Male	Male	Male	Female
BMI (kg/m^2)	22.8	29.4	30.9	32.0
ASA PS	III	IV	III	III
Liver disease	Alcoholic & HCV cirrhosis	Alcoholic cirrhosis & Hepatocellular carcinoma	Alcoholic cirrhosis & Hepatocellular carcinoma	Nonalcoholic steatohepatitis
MELD Na$^+$	20	23	25	13
Cirrhotic complication	Encephalopathy, ascites, jaundice	Splenomegaly, ascites, jaundice	Splenomegaly, thrombocytopenia, esophageal varices, ascites	Encephalopathy, refractory ascites, portal hypertension, jaundice
Past medical history	HTN, bicuspid aortic valve with mild regurgitation	HTN, DM, pulmonary emphysema	HTN, DM, obesity	HTN, DM, obesity, anemia
Blood loss (mL)	1,900	5,000	500	4,000
Fluid therapy (mL)	2,000	5,500	7,000	8,500
Blood products (intraoperative)	6 RBC, Cell Saver 2,000 mL (Hct 38%), 3 PC, FFP 20 U, PCC 500 UI, Fibrinogen 4 g	9 RBC, Cell Saver 2,100 mL (35%), 4 PC, FFP 22 U, PCC 1,000 U, Fibrinogen 7 g, Albumin 10 g	2 RBC, FFP 8U	4 RBC, Cell Saver 1,550 mL (Hct 25%), FFP 8 U, Fibrinogen 3 g, Albumin 20 g
Max. intraoperative NA	0.68 mcg/kg/min	0.61 mcg/kg/min	0.15 mcg/kg/min	N/A
Max. second vasopressor	N/A	N/A	Terlipressin (0,1ug/kg/h)	N/A
Cold ischemia time (min)	425	421	267	271
Warm ischemia time (min)	71	90	55	66
Time HOPE machine (min)	243	350	251	201
Duration of surgery (min)	540	590	440	450
Duration of anesthesia (min)	620	660	520	510
Extubation at the end	No	No	Yes	Yes
Length of intubation (day)	1	9	N/A	N/A
Major postoperative complications	No	Hyperbilirubinemia	No	No
Reintervention required	No	No	No	No
Length of ICU stay (day)	5	20	2	2
Length of hospital stay (day)	11	40	10	17
Mortality at 30 days	No	No	No	No
Follow-up (day)	93	86	74	31

ASA PS, American Society Association Physical Status; BMI, body mass index; DM, diabetes mellitus; FFP, fresh frozen plasma; ICU, intensive care unit; HCV, hepatitis C virus; HOPE, hypothermic oxygenated machine perfusion; HTN, hypertension; MELD, model for end-stage liver disease; NA, noradrenaline; N/A, not applicable; PC, platelet concentrates; PCC, prothrombin complex concentrate; RBC, red blood cell.

Local Health Unit of São José between February and April 2024. The Ethics Committee approved this study (INV 628). Informed consent was obtained from all participants.

Data collected from medical records included demographics, clinical profile (past medical history and liver disease etiology), preoperative assessment American Society of Anesthesiologists (ASA) physical status and preoperative model for end-stage liver disease (MELD) score, surgical and anesthesia details (techniques used and intraoperative monitoring), perioperative management (blood products and inotropic support), postoperative course (duration of intubation, intensive care unit [ICU] stay and hospital stay) and outcomes (short-term recovery, mid-term recovery, and 30-day mortality).

Over the three-month period analyzed, four patients underwent total robotic liver transplantation with organs sourced from deceased donors. The same surgical team performed all procedures under general anesthesia. Patient demographics, operative details, anesthesia details, and intraoperative complications are compiled in Table 1. Patients' ages ranged from 51 to 69 years. Their cirrhosis was primarily due to alcohol use, hepatitis C virus infection, hepatocellular carcinoma, or nonalcoholic steatohepatitis.

Monitoring and vascular catheters

Intraoperative monitoring

In all patients, monitoring included pulse oximetry, end-tidal CO_2, a three-lead electrocardiography, invasive arterial pressure, central venous pressure, and bispectral index. Neuromuscular blockade was monitored with train-of-four and post-tetanic counts. Continuous monitoring of temperature, urine output, and arterial blood gases was conducted hourly. A PiCCO system provided minimally invasive hemodynamic monitoring (Fig. 1). Blood tests including complete blood count and coagulation tests were performed at least at the following three key stages: post-hepatectomy, at the time of reperfusion, and prior to surgical closure. Additionally, a thromboelastogram was used to assess coagulation status at the time of reperfusion.

Vascular catheters

During robotic liver transplantation procedures, we used the following vascular catheters: a left radial arterial catheter, a right femoral arterial catheter connected to the PiCCO system for advanced hemodynamic monitoring, a peripheral venous catheter, and a four/five lumens jugular venous catheter. All catheters were inserted under ultrasound guidance. In addition, a rapid infusion venous system was used for rapid volume administration. In one patient, a standard rapid infusion catheter was inserted into the basilic/cephalic vein. In the remaining three patients a Swan-Ganz introducer sheath was placed via ultrasound guidance into the internal jugular vein (two patients) or axillary vein (one patient).

Induction and maintenance

Anesthetic induction

Patients underwent pre-oxygenation followed by rapid sequence induction using a combination of fentanyl, propofol, and rocuronium. Orotracheal intubation was performed and a nasogastric tube was inserted.

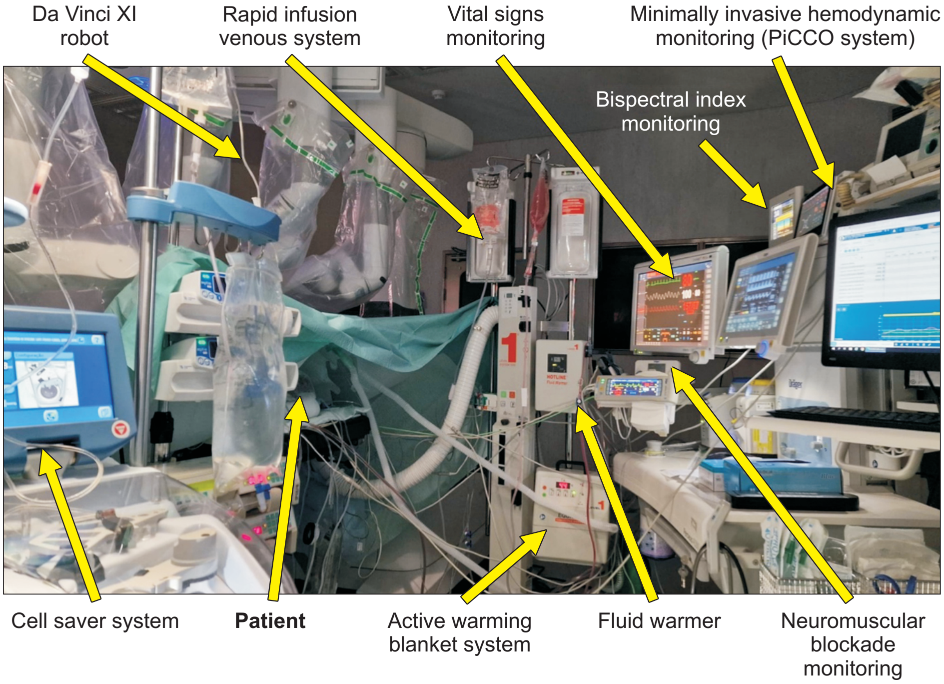


Fig. 1. Complexities in anesthetic management during robotic liver transplantation: navigating limited access and space with precision monitoring.

Maintenance of anesthesia

Sevoflurane was used with the minimum alveolar concentration titrated by bispectral index. Rocuronium (0.4 mg.kg^{-1}.hour^{-1}) and fentanyl (0.7 μg.kg^{-1}.hour^{-1}) were administered post anesthesia induction. Rocuronium dosage was adjusted to maintain a deep blockade, indicated by a post-tetanic count of less than two.

Intraoperative management

Antibiotic prophylaxis was administered per the protocol, including cefotaxime 2 g and ampicillin 2 g. Antithrombotic prophylaxis consisted of elastic compression stockings and intermittent pneumatic compression socks.

Special procedures

Ascites drainage was required in two cases before pneumoperitoneum insufflation. Drained fluid exceeded 5 liters, requiring administration of albumin. Lung recruitment maneuvers were performed after anesthesia induction to manage airway pressures as hemodynamics allowed. Despite prolonged pneumoperitoneum, no ventilation difficulty was noticed.

Fluid and electrolyte management

PiCCO monitoring and repeated blood gas analysis were used to guide intraoperative management. Goal-directed fluid therapy was employed using a PlasmaLyte® balanced crystalloid solution. Fluids and blood products were warmed using a Hotline™ fluid warmer.

Blood loss management

Intraoperative blood loss ranged from 1,000 to 5,000 mL. It was managed with blood products including fresh frozen plasma, red blood cells, fibrinogen, platelets, and prothrombin complex guided by laboratory results. A cell saver device was used for blood recovery when not contraindicated.

Pain and nausea management

Fentanyl infusion was administered during surgery. Intravenous morphine (4 mg), metamizol (2 g), tramadol (200 mg), and ropivacaine (0.75%) were administered at the end of the surgery. Ondansetron was used for nausea and vomiting prophylaxis.

Surgical considerations

All surgical procedures were conducted using a Da Vinci XI system. Prior to docking, patients were positioned in a reverse Trendelenburg position, typically between 10 and 15 degrees. The precise angle was confirmed using a calibrated smartphone application. Robotic assistance was performed through five to six ports strategically placed.

The piggyback technique was used to detach the liver from the inferior vena cava (IVC). After carefully dissecting and preparing the liver's blood vessels and fully mobilizing the liver, portal and hepatic veins were stapled and cut, leading to complete removal of the liver (total hepatectomy). Each patient's liver was removed through the camera port incision, which was enlarged to 7–10 centimeters. This incision allowed for extraction of diseased liver and introduction of donor liver. Subsequently, the port site was promptly closed to re-establish pneumoperitoneum (Fig. 2). Implantation of the liver graft then began, starting with a side-to-side anastomosis of the IVC, followed by arterial and biliary anastomosis [7]. All donor livers were optimally prepared using a hypothermic oxygenated machine perfusion (HOPE) machine prior to transplantation [8]. Throughout the reperfusion phase, serious adverse events such as severe hypotension and arrhythmias were not observed.

Postoperative outcomes

Extubation in the operating room was successfully performed in 50% (two out of four) of patients. Post-surgery, all patients were admitted to a level III ICU.

Postoperative analgesia

For those extubated, effective postoperative pain management was achieved using lower doses of intravenous morphine (4 mg), tramadol (200 mg), metamizole (2 g), and ropivacaine (0.75%) at operative ports. During a 48-hour postoperative period, patients received metamizole (2 g every 12 hours) and tramadol as needed for rescue analgesia. Pain levels both at rest and during activity were consistently reported as well-controlled.

Postoperative hospitalization

The length of hospitalization varied, ranging from 10 days

Fig. 2. Surgical ports for robotic liver transplantation.

to 40 days. Patient two, a 66-year-old male with diabetes and pulmonary emphysema, MELD of 23, and international normalized ratio of 2.0, had a hospital stay of 40 days. This patient received a 69-year-old steatotic graft. He had persistent oozing during 590 minutes of surgery, justifying a significant blood loss (5,000 mL) without any acute hemorrhagic event. The patient needed prolonged ventilatory support and had persistent hyperbilirubinemia that subsequently improved.

Survival rate

The 30-day survival rate for the cohort was 100%, highlighting the effectiveness of anesthetic and surgical approaches.

Comparison with conventional open DDLT technique

Anesthetic management for liver transplantation, whether robotic or conventional, is complex. It requires meticulous planning and execution. Below is a comparison of anesthetic approaches for total robotic liver transplant and conventional open DDLT.

Preoperative considerations

1) patient selection: robotic liver transplant typically involves patients with fewer comorbidities due to its technical complexity and longer operative time, while conventional open DDLT technique usually includes patients with more advanced liver disease and comorbidities; 2) preoperative assessment: robotic liver transplant and conventional open DDLT have similar preoperative assessment, although a robotic liver transplant has an additional focus on patient's ability to tolerate pneumoperitoneum and a longer procedure duration during the learning phase.

Intraoperative considerations

1) positioning: in robotic liver transplant, patients are placed in a reverse Trendelenburg position to optimize surgical access, which can impact hemodynamics and respiratory mechanics, while in conventional open liver transplant, patients are placed in a less pronounced reverse Trendelenburg position (which is less likely to cause significant hemodynamic or respiratory changes) and can be repositioned during surgery; 2) anesthetic technique: robotic liver transplant and conventional open DDLT have a similar anesthetic technique, although robotic liver transplant needs a close monitoring of hemodynamics due to effects of pneumoperitoneum and positioning as well as deeper neuromuscular blockade. The use of robotic arms with extended reach, improved range of motions, and enhanced visualization capabilities may result in less hepatic mobilization with fewer hemodynamic impact than manual mobilization. Close monitoring is required due to inability to mobilize the surgical table with potential necessity of an emergency undocking and conversion to open surgery (due to a risk of uncontrolled or massive bleeding or inability to provide adequate hemodynamic support); 3) ventilation: robotic liver transplant ventilation requires adjustments and recruitment maneuvers to manage increased intra-abdominal pressure and maintain adequate ventilation, while conventional open DDLT technique requires standard mechanical ventilation; 4) fluid management: robotic liver transplant and conventional open DDLT have similar fluid management, although robotic liver transplant needs to avoid volume overload while maintaining adequate perfusion and consider a decreased urinary output resulting from pneumoperitoneum.

Postoperative care

Regarding recovery and pain management, patients may experience less postoperative pain and quicker recovery with a robotic approach due to its minimally invasive nature, while conventional open liver transplant may imply longer recovery time and more intensive pain management due to larger surgical incision and more extensive tissue manipulation.

Complications

Specific risks of robotic liver transplant include complications related to pneumoperitoneum (e.g., venous air embolism, increased intra-abdominal pressure, increased $PaCO_2$) and positioning (e.g., nerve injuries). Specific risks of conventional open liver transplant include higher risk of wound infections and incisional hernias.

DISCUSSION

This study holds the distinction in that it presents inaugural series of robotic liver transplants in Europe to the best of our knowledge. The introduction of this therapeutic technique represents a considerable challenge, both surgically and anesthetically. At this foundational phase, our aim was to outline anesthesia protocols implemented in these initial cases, to consider how they diverged from traditional methods, to address challenges faced, and to identify areas for potential future enhancements.

Robotic surgery has revolutionized surgical interventions, offering a minimally invasive alternative to traditional open surgeries [5]. This advancement necessitates parallel developments of surgical and anesthetic techniques.

Patients undergoing a robotic surgery typically experience less postoperative pain than patients undergoing a conventional open surgery due to smaller incisions [1]. Our observations indicated effective pain management postoperatively with metamizole (2 g every 12 hours) and tramadol for rescue analgesia, contrasting with the typically more intense pain management following open liver transplants. Additionally, robotic surgery has been associated with fewer postoperative wound complications than patients undergoing a conventional open surgery [1,2,4,5,9], in line with our patient series.

Studies comparing robotic surgery to open liver surgery have reported less blood loss and shorter hospital stays in the former

[2,10]. Recent expert consensus has endorsed robotic surgery for donor hepatectomy, highlighting its safety and benefits [4,11]. Although our data did not indicate reduced hemorrhagic losses in robotic liver transplants, it might be due to a learning curve associated with this technique. Both operative time and warm ischemia time decreased with subsequent cases, suggesting a learning effect.

Challenges in robotic liver transplantation

While robotic liver transplantation offers numerous benefits, it also presents unique challenges (Fig. 3), including its inability to reposition patients during surgery, limited patient access, restricted operating room space, and potentially longer procedure times during the initial learning phase. Additionally, hemodynamic and respiratory effects of pneumoperitoneum, risk of gas embolism, and occult blood loss are notable concerns [4,5]. To address these challenges, non-technical skills such as anticipation, situational awareness, and effective multidisciplinary communication are essential. These skills play a critical role in managing complexities and potential emergencies that arise during prolonged surgeries.

Intraoperative care and fluid management

Intraoperative monitoring of PiCCO values is essential for guiding vasopressor support and fluid therapy decisions. In cases with a low peripheral vascular resistance, norepinephrine is the vasopressor of choice. Fluid therapy aims to strike a balance between volume therapy and goal-directed fluid boluses, improving intravascular volume and circulatory flow. We opted for balanced electrolyte solutions over lactated Ringer's solution and NaCl (0.9%) [4].

HOPE in donor liver preparation

All donor livers underwent preparation using HOPE machine, which could mitigate post-reperfusion syndrome and electrolyte imbalances [8]. The HOPE machine method also correlated with a reduced need for vasopressors post-reperfusion [8], in line with decreased norepinephrine usage and lower serum potassium levels in our cohort.

Intensive care following robotic liver transplantation

In our initial series of robotic liver transplants, two out of four patients required extended ventilation in the ICU. These transplants were the first robotic transplants our team performed. Transplantation procedures lasted almost ten hours and involved substantial fluid management challenges. The complexity and length of these procedures likely justified the need for prolonged invasive mechanical ventilation.

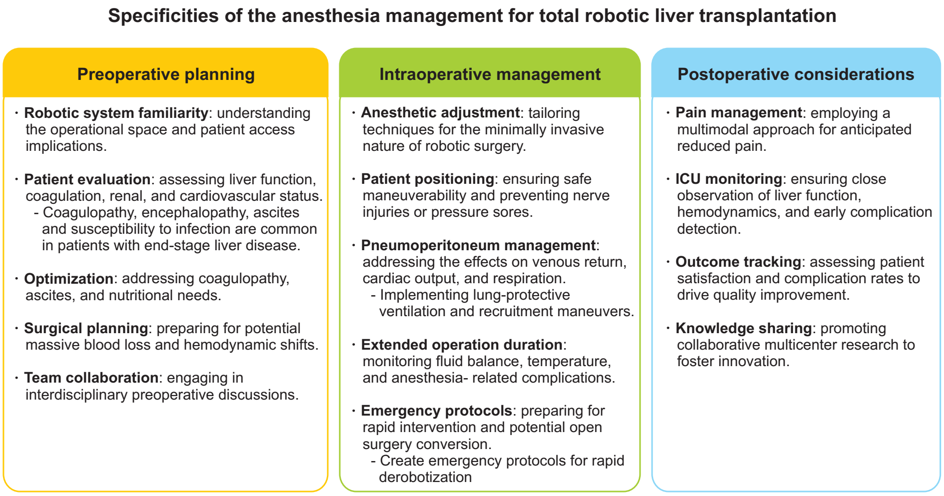
Complications and patient selection

A notable postoperative complication was observed in one individual with persistent hyperbilirubinemia after transplantation. This individual, deemed high risk with an ASA classification of IV, underwent a protracted surgery lasting nearly 10 hours, which was further complicated by significant blood loss. This case accentuates the imperative of judicious graft and patient selection, particularly during the early phase of implementing robotic liver transplantation. It also suggests the potential necessity for intraoperative conversion to laparotomy in the event of insufficient hemostatic control or persistent hemodynamic instability that cannot be improved.

Limitations

This investigation was conducted at a single institution. Its limited sample size necessitates a prudent interpretation of its findings. An additional constraint was the study's retrospective observational design, which precluded a direct comparative analysis with traditional open surgical techniques.

Furthermore, the interpretation of our outcomes must account for incremental learning curve inherent to the adop-



Specificities of the anesthesia management for total robotic liver transplantation

Preoperative planning

- **Robotic system familiarity**: understanding the operational space and patient access implications.
- **Patient evaluation**: assessing liver function, coagulation, renal, and cardiovascular status.
  - Coagulopathy, encephalopathy, ascites and susceptibility to infection are common in patients with end-stage liver disease.
- **Optimization**: addressing coagulopathy, ascites, and nutritional needs.
- **Surgical planning**: preparing for potential massive blood loss and hemodynamic shifts.
- **Team collaboration**: engaging in interdisciplinary preoperative discussions.

Intraoperative management

- **Anesthetic adjustment**: tailoring techniques for the minimally invasive nature of robotic surgery.
- **Patient positioning**: ensuring safe maneuverability and preventing nerve injuries or pressure sores.
- **Pneumoperitoneum management**: addressing the effects on venous return, cardiac output, and respiration.
  - Implementing lung-protective ventilation and recruitment maneuvers.
- **Extended operation duration**: monitoring fluid balance, temperature, and anesthesia- related complications.
- **Emergency protocols**: preparing for rapid intervention and potential open surgery conversion.
  - Create emergency protocols for rapid derobotization

Postoperative considerations

- **Pain management**: employing a multimodal approach for anticipated reduced pain.
- **ICU monitoring**: ensuring close observation of liver function, hemodynamics, and early complication detection.
- **Outcome tracking**: assessing patient satisfaction and complication rates to drive quality improvement.
- **Knowledge sharing**: promoting collaborative multicenter research to foster innovation.

Fig. 3. Orchestrating anesthesia for robotic liver transplantation: A tri-phasic blueprint from preoperative planning to postoperative recovery. ICU, intensive care unit.

tion of this novel technology. To ascertain advantages, safety profile, and economic viability of comprehensive robotic liver transplantation, further research across multiple institutions and a broader cohort of subjects is imperative.

Conclusions

This initial case series underscores the promising potential of robotic technology in liver transplantation, showcasing its viability. The technique demonstrated encouraging short-term outcomes, notably expediting patients' resumption of daily activities. Nonetheless, the importance of careful patient selection during early stages of the learning curve is evident as it may enhance outcomes. Furthermore, the possibility of converting to laparotomy should remain an option in the event of surgical or anesthetic difficulties. These cases highlight the pivotal role of anesthetic management in ensuring the success of complex and delicate surgical procedures that incorporate robotic assistance.

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CONFLICT OF INTEREST

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Conceptualization: AD, VK, RP. Data curation: AD, VK, RP. Methodology: AD, VK, RP. Visualization: AD, VK, RP. Writing - original draft: AD, VK, RP. Writing - review & editing: All authors.

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