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Emerging Technology

Anesthetic Considerations for Robotic Liver Transplantation

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Liver transplantation has traditionally been performed through a large, bilateral subcostal incision. Recently, liver transplant programs across the world, including our own, have reported successful liver transplants via total robotic approaches on recipients with low Model for End-stage Liver Disease scores and preexisting abdominal wall laxity. This review discusses the unique anesthetic considerations of robotic liver transplantation based on our group's initial experience with this novel surgical approach. Robotic liver transplantation presents a unique set of considerations and challenges for the anesthesiologist, and a thorough understanding of liver disease, liver transplant surgery, venovenous bypass, and the various implications of robotic surgery is essential to ensure optimal patient outcomes. Specific management topics discussed here include appropriate patient selection, preoperative assessment, and intraoperative management. We also discuss certain theoretical and actual challenges that our group has experienced.
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LIVER TRANSPLANTATION (LT) was first performed by Thomas Starzl in 1963.[1] Since then, the indications for LT have expanded. Currently, LT is indicated in patients with acute liver failure, cirrhosis, liver neoplasms, and metabolic disorders.[2-6] In 2022, 9,527 liver transplants were performed in the United States alone.[7] Alcohol-associated liver disease continues to be the primary driver of transplantation in the United States, comprising 37.5% of candidates.[7]

Historically, LT has been performed via a Chevron incision, which consists of a bilateral subcostal incision with an upper midline T extension.[8,9] However, these large incisions predispose patients to higher postoperative pain scoring, worsening postoperative respiratory dysfunction, long hospital lengths of stay and, in certain circumstances, may impose long-term negative psychological effects.[10-13] The field of robotic liver surgery (RLS) has grown rapidly since the first reported robotic liver resection in 2003.[14] RLS has shown to be safe and feasible and offers clear advantages over open surgery in terms of a reduction in blood loss,[11,15-17] hospital length of stay,[18,19] and pain scores.[20] With the growing volume of RLS programs across the world, liver transplant centers have followed suit to establish robotic liver transplantation (RLT) programs.

Since 2022, there have been a handful of reports of RLT around the globe using both living donor partial grafts and deceased donor whole grafts.[20-23] Our transplant center has been a pioneering program for the deceased donor whole graft technique.[22] While there are a limited number of case reports and case series that focus on the surgical

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considerations for RLT,[20-23] to our knowledge, there are currently no articles that focus primarily on the anesthetic considerations for these surgeries. Based on our early experience, here we report our liver anesthesia group's approach to RLT with deceased donor whole grafts. We are the only U.S. center and one of three centers worldwide to have performed deceased donor RLT.[22,23]

Institutional Experience

During the past 1.5 years, we have performed six robotic liver transplants using deceased donor grafts. Three of these were hybrid (i.e., the total hepatectomy was performed robotically and the implantation was performed through a small upper midline incision from the subxiphoid area to around umbilicus of approximately 15-20 cm in length). In the other three, hepatectomy and implantation were performed robotically (total RLT). Both the hybrid and total RLT techniques used the same port sites and midline incision (Fig 1). Among the series of six RLTs performed, No. 1, No. 2, and No. 4 were done as hybrid procedures, and No. 3, No. 5, and No. 6 were done as total RLT. All six patients had uneventful recoveries with no robot-related complications, retransplantations, or deaths. All six patients had functioning liver grafts at the last follow-up. Venovenous bypass (VVB) was used in the three total RLT patients.

Surgical Considerations

Patient selection

Appropriate patient selection for deceased donor whole graft RLT, especially in the early era of this surgical approach, is critical.[22]

BMI and Body Habitus

Excess body mass and abdominal wall rigidity reduce intraabdominal working space and hinder the ability to maintain pneumoperitoneum.[24-26] At our institution, patient criteria for RLT include upper limits of body mass index (BMI) of 25 to 30 kg/m^2 in patients who also have coexisting abdominal wall laxity (i.e., postpartum or history of ascites).[22] This coexisting abdominal wall laxity allows for better creation of pneumoperitoneum and, therefore, better surgical visualization and exposure.

Model for End-stage Liver Disease Score

Patients considered for deceased donor whole graft RLT have a low Model for End-stage Liver Disease (MELD) score (defined as <25) with portal hypertension but without portal vein and hepatic artery thrombosis.[22] Patients who have coexisting portal hypertension are selected for RLT because they typically have a rich network of portal collateralization that allows them to better tolerate the prolonged portal vein clamping during RLT, which results in less hemodynamic swings during the course of surgery.

Liver Graft Size

Small donor livers (<2,000 g) are selected to avoid a large recipient midline incision to introduce the donor graft into the abdomen. Smaller donor grafts also reduce the time required for positioning the graft before performing vascular and biliary anastomoses. [22]

Surgical Technique

Currently, there are two published surgical techniques for deceased donor whole graft RLT.[22,23] The full details of these surgical techniques are beyond the scope of this report. However, it is important to highlight that while these two reports

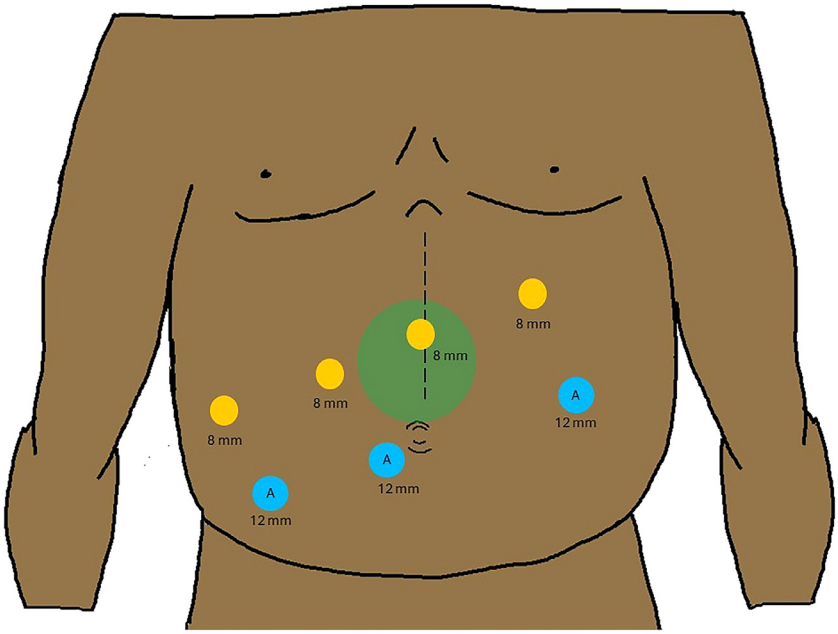

Fig 1. Illustration of port placement. *Green circle*, gel port location; *dotted line*, midline incision.

include cases performed in three different countries (U.S., Italy, and Portugal), the reports were nearly identical in patient selection criteria and operative technique for hepatectomy and implantation with the only major difference being the preference of one center to use VVB while the inferior vena cava (IVC) was clamped for the caval anastomosis. The technique of the caval anastomosis itself was identical in the two reports, with both of them describing total clamping of IVC with side-to-side anastomosis using monofilament permanent suture.[22,23] In this report, we describe the anesthetic approach to the side-to-side cavocavostomy approach with VVB, which is currently the technique of choice at our institution.

Anesthetic Considerations

Preoperative assessment

The anesthetic preoperative assessment for RLT closely mirrors the preoperative assessment for open liver transplants and is based on both institutional practice and international societal practice guidelines, with the cardiac workup being the primary determinant of eligibility for RLT from an anesthesiologist perspective (Fig 2).[27–29]

Intraoperative management

A list of intraoperative anesthetic considerations for RLT is shown in Table 1.

Room preparation

In preparation for RLT, a robotic operating room was modified for liver transplantation. Specifically, space was created in the periphery of the room for two Da Vinci robot operating consoles, as well as a docking location for the Da Vinci Xi Robot (Intuitive Surgical Inc., Sunnyvale, CA) on the opposite side of the room. Additional ancillary equipment specific to LT includes a crash cart, ultrasound machine, Belmont infuser, VVB circuit, and ROTEM Sigma machine. A full overview of the room is shown in Fig 3.

Monitors, Laboratory Assessment, and Anesthetic Technique

Once the patient arrives in the operating room, standard American Society of Anesthesiologists monitors are placed. Invasive monitors include central venous pressure (CVP) and arterial blood pressure (ABP) with pulse pressure variation (PPV). The use of a pulmonary artery catheter is not routine for RLT. Electrode defibrillator pads (Conmed Corporation, Largo, FL) are placed and connected to the Lifepak 15 defibrillator (Physio-Control, Redmond, WA) in case of ventricular arrhythmia development during graft reperfusion. Intraoperative transesophageal echocardiography (TEE) is used to monitor heart function in real time throughout the surgery. Point-of care laboratory testing (arterial blood gas, complete blood count, prothrombin time, international normalized ratio, partial thromboplastin time, fibrinogen, thrombin time, and D-dimer) and viscoelastic testing via ROTEM-Sigma (Werfen, Bedford, MA) are performed hourly during RLT per our institutional protocol. We use the same institutional point-of-care laboratory testing protocol that we use for our open LT.

After induction, we use a balanced approach for maintenance anesthesia with inhalational agents and intravenous (IV) fentanyl infusion. We use bolus dosing of rocuronium to titrate the train-of-four ratio to a goal of zero throughout the surgery. We monitor the depth of neuromuscular blockage with the

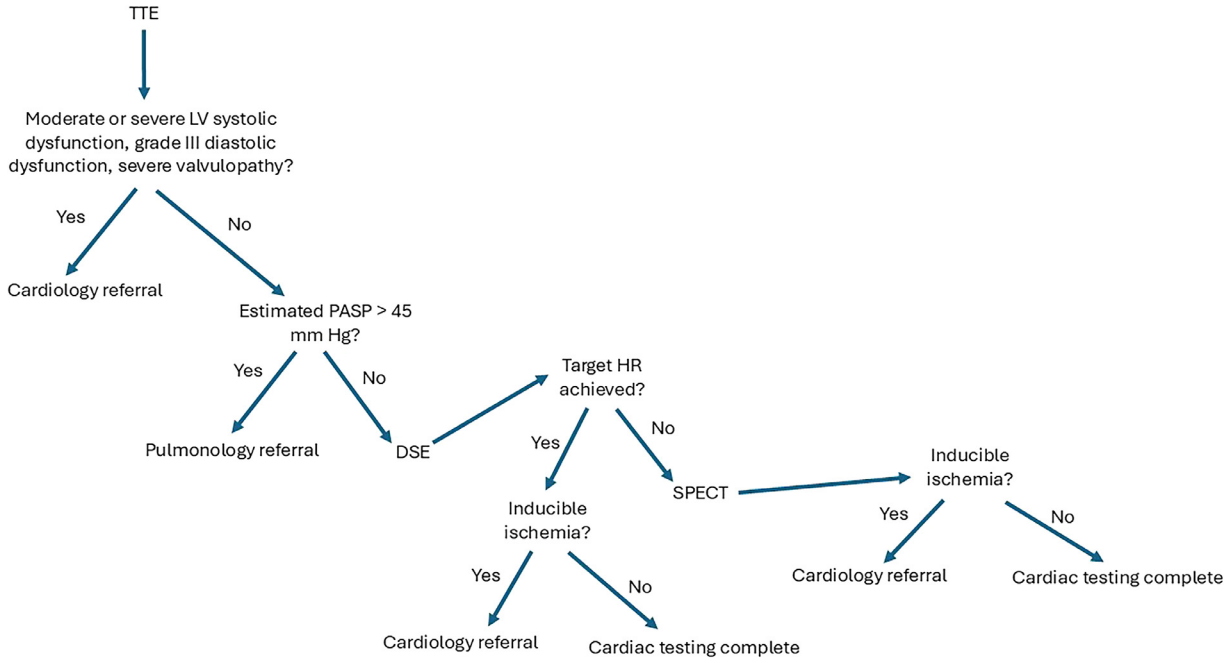

Fig 2. Preoperative cardiac assessment for robotic liver transplantation. TTE, transthoracic echocardiogram; LV, left ventricular; PASP, pulmonary artery systolic pressure; DSE, dobutamine stress echocardiogram; SPECT, single-photon emission computer tomography; RLT, robotic liver transplantation.

Table 1
Summary of Anesthetic Considerations for Robotic Liver Transplantation

Consideration	Anesthetic Approach
Monitors	• Standard ASA monitors: 5-lead ECG, pulse oximeter, $EtCO_2$ monitor, non-invasive BP cuff, core temperature (bladder) • Invasive: arterial blood pressure with PPV, CVP monitoring, TEE
Laboratory assessment	• POC laboratory testing: CBC, PT/INR, PTT, fibrinogen, thrombin time, D-dimer, ABG with electrolytes and lactate • Viscoelastic testing: ROTEM-Sigma, INTEM, EXTEM, FIBTEM, APTEM
Line placement	• Peripheral IV: preoperative placement, used for induction • Radial arterial line catheter (20 gauge) • Quad-lumen CVC (8.5Fr): placement in RIJ, used for vasoactive infusions • Hemodialysis catheter (13Fr): placement in RIJ, used as outflow cannula for VVB circuit • Rapid Infusion catheter (8.5Fr or 7Fr): used for rapid volume resuscitation; connected to Belmont infuser • Femoral venous line (17Fr): placed by surgical team for venous drainage for VVB
Patient positioning	• Supine with leg spreaders • Steep reverse Trendelenburg position to facilitate surgical exposure and minimize hepatic vascular engorgement
Fluid management	• While level/supine, target CVP 7-10 mmHg • While in steep reverse Trendelenburg positioning: CVP goal modified to <5 mmHg • Fluid administration: combination of crystalloid (lactated Ringer and normal saline) and colloids (5% albumin) to meet CVP and perfusion goals • Blood products: PRBC, FFP, cryoprecipitate, platelets, and antifibrinolytics based on standard protocols
Thermoregulation	• Cocoon CWS 5000 warming device
Ventilator management	• Minute ventilation increased with pneumoperitoneum creation • Pressure-control ventilation used if peak pressures are increased with steep RT positioning
Venovenous bypass	• Inflow cannula: 17Fr femoral venous catheter • Outflow cannula: 13Fr hemodialysis catheter in RIJ • Goal flows: 1.8-2.2 L/min
Anticoagulation strategy	• Goal ACT >200 seconds during VVB • IV heparin bolus (2,000 IU) administered before initiation of VVB • Re-dose with monitoring ACT every 30 min • Protamine reversal after VVB

Abbreviations: ABG, arterial blood gases; ACT, activated clotting time; APTEM, aprotinin-activated thromboelastometry; ASA, American Society of Anesthesiologists; BP, blood pressure; CBC, complete blood count; CVC, CVP, central venous pressure; ECG, electrocardiogram; $EtCO_2$, end-tidal CO_2; EXTEM, extrinsically-actived thromboelastometry; FIBTEM, fibrin-activated thromboelastometry; FFP, fresh frozen plasma; INTEM, intrinsically-activated thromboelastometry; IV, intravenous; POC, point-of-care; PPV, pulse pressure variation; PRBC, packed red blood cell; PT/INR, prothrombin time/international normalized ratio; PTT, partial thromboplastin time; RIJ, right internal jugular; ROTEM-Sigma, rotational thromboelastometry Sigma; RT, reverse Trendelenburg; TEE, transesophageal echocardiography; VVB, venovenous bypass.

TwitchView Monitor (Blink Device Company, Seattle, WA) for electromyography-based quantitative monitoring. The deep level of neuromuscular blockade that is maintained optimizes surgical exposure and ventilatory management in the setting of steep reverse Trendelenburg (RT) positioning and pneumoperitoneum. Sugammadex is used for neuromuscular blockade reversal at the case end.

Line placement

A peripheral IV catheter is placed preoperatively and is used for anesthetic induction. A 20-gauge arterial line is placed in the radial location for invasive blood pressure monitoring. The decision to place this arterial line preinduction versus postinduction is made on a case-by-case basis according to patient comorbidities. After induction and intubation, central venous access is placed via a double-stick approach in right internal jugular (IJ) vein. We place an 8.5Fr quad-lumen line (Teleflex, Wayne, PA) and a 13Fr temporary hemodialysis catheter (Medtronic, Minneapolis, MN). The quad-lumen line is used for vasoactive infusions. The hemodialysis catheter is used as the outflow conduit for the VVB circuit. An 8.5Fr or 7Fr rapid infusion catheter (RIC) (Teleflex, Wayne, PA) is placed in an antecubital vein as a volume line for rapid resuscitation. The RIC line is connected directly to an RI-2 rapid infuser (Belmont Medical Technologies, Billerica, MA), which provides rapid fluid infusion and warming.

A nasogastric tube (NGT) is placed to facilitate gastric decompression during surgery and to allow for the administration of immunosuppressive medications in the immediate postoperative period. If blind passage of the NGT is difficult, we use a video laryngoscope-assisted method for NGT placement. With video laryngoscopy, the hypopharyngeal soft tissue and in situ endotracheal tube can be retracted anteriorly, which creates an unobstructed pathway for the NGT to pass into the upper esophagus under indirect visualization.

Patient positioning

The patient is initially positioned in the supine position on the TS7000dV DaVinci robot–compatible surgical table (Hillrom, Chicago, IL). Legs are placed in leg spreaders to allow for easier surgical access to the abdomen, and both arms are tucked. Because the patient's arms are inaccessible during surgery, the RIC line and arterial line are confirmed to be functioning properly immediately after arm positioning. After robotic arm placement, the patient is positioned to a steep reverse Trendelenburg (RT) position at 14 degrees to facilitate surgical exposure and reduce hepatic vascular engorgement.

Fluid Management

While the patient is in the level position, we target a normal CVP of 7 to 10 mmHg to maintain vital organ perfusion while reducing the risk of surgical bleeding.[30-32] Higher CVP values greater than 10 mmHg are avoided due to an increase in the hydrostatic resistance to blood flow through the liver, which increases the likelihood of venous bleeding, particularly during

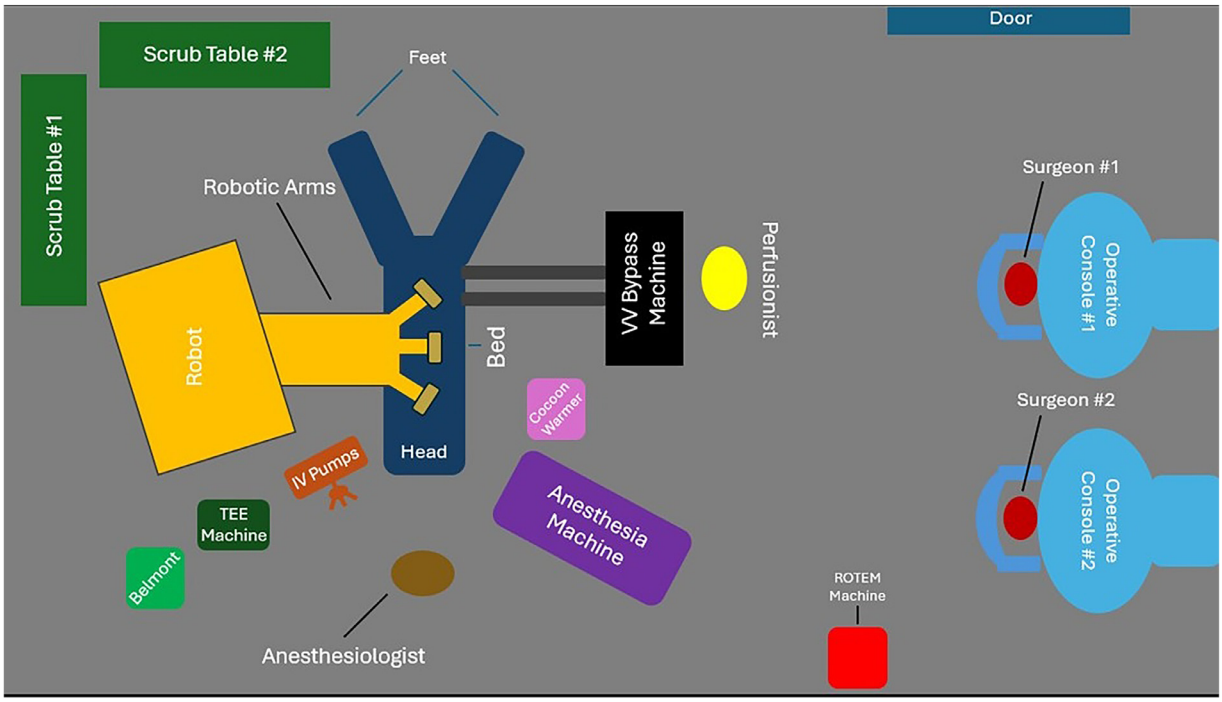

Fig 3. Layout of the operating room for robotic liver transplantation.

the dissection phase. If the CVP does climb above our goal of 10 mmHg, further fluid resuscitation is paused to allow the CVP to passively drift back down. The use of diuretic therapy in this setting is not routinely used.

Once the patient is positioned in steep RT as described above, in combination with the caval compression caused by carbon dioxide (CO_2) insufflation, the CVP may drop below 7 mmHg even despite aggressive fluid resuscitation. In these instances when RT positioning is required, we temporarily transition our CVP goal to a lower pressure of 5 mmHg or less. This low CVP strategy has been shown to be temporarily safe and effective during open liver transplantation while recognizing that excessively prolonged low CVP values may predispose that patient to hypotension and organ hypoperfusion.[33-37] Once the patient is leveled out again, we return to our CVP goal of 7 to 10 mmHg.

In addition to CVP, we routinely use left ventricular end-diastolic volume (LVEDV) assessment on TEE and PPV from the ABP tracing to assess overall volume status.[38,39] An LVEDV less than 46 mL in women and 62 mL in men is the typical threshold for further fluid resuscitation.[40,41] We use a biplane method to make this echocardiographic calculation by first measuring the LVEDV in the mid-esophageal four-chamber view and then again in the mid-esophageal two-chamber view. We then average these two values. In regards to PPV, a value greater than 11 is our threshold for further fluid resuscitation.[39] However, when the patient is in the steep RT positioning and cardiac filling volumes are transiently decreased as a result of this positioning, we will temporarily accept lower LVEDV and higher PPV values until supine positioning is reestablished.

We resuscitate the patient with a combination of crystalloid and colloid fluids. Lactated Ringer (LR), normal saline (NS), and 5% albumin solutions are all used. Because withholding transfusion of blood and blood products is a strong predictor of overall survival after LT, we take a conservative approach to allogenic blood product transfusion based on information derived from intraoperative arterial blood gas, complete blood count, coagulation point-of-care testing, and ROTEM Sigma sampling.[42,43] A hemoglobin of 7 g/dL or hematocrit of 21% is our standard threshold for packed red blood cell transfusions.[44] Transfusions of fresh frozen plasma, cryoprecipitate, platelets, and antifibrinolytics are based on previously published protocols.[45] To date, our center has not used intraoperative blood salvage autotransfusion during RLT, but doing so would be feasible in the future by incorporating the following additional components: suction irrigator instrument, 5-1 connector, additional suction tubing, and Neptune 3 system (Stryker, Kalamazoo, MI). Another consideration regarding the use of intraoperative blood salvage autotransfusion during RLT is that some recipients have low native MELD scores with coexisting hepatocellular carcinoma at the time of transplant. While our institution does not routinely use cell savage during LT in the setting of malignancy out of concern for tumor cell reintroduction and recurrence, we recognize that there is emerging evidence that cell savage may be used safely in this setting.[46]

Thermoregulation

During our initial experience with RLT, we struggled with hypothermia when using our standard convective forced-air warming devices. The main challenge associated with these conventional warmers was inadequate patient coverage,

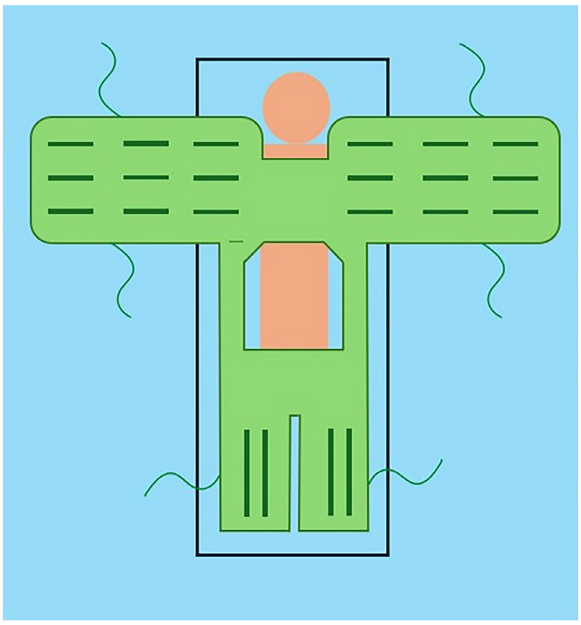

Fig 4. The Cocoon warming system includes a full-body warming blanket with an abdominal cutout.

especially along the lower extremities, when positioned in the leg spreaders. We subsequently shifted our preferred warming device to the Cocoon CWS 5000 convective warming device (North Geelong, Victoria, Australia) with better thermoregulatory success. This Cocoon warming system provides many advantages relative to standard warmers, including its range of four total temperature settings: 34˚C, 40˚C, 43˚C, and 46˚C. The 46˚C setting provides a temporary warming "boost" by heating the blanket to 46˚C for 10 minutes before defaulting back to 43˚C. Another advantage of the Cocoon warmer is superior coverage of the upper and lower extremities (Fig 4). The better patient surface coverage provided with this warming blanket seems to reduce the overall radiation-associated hypothermia. Also, the Cocoon warming blanket provides a large cut-out section over the chest and abdomen, which allows for adequate surgical access to the abdomen without any disruption to patient warming.

Ventilator management

Once pneumoperitoneum is established, the ventilator settings are adjusted to account for the increased component of dissolved carbon dioxide in the blood. Minute ventilation is increased by adjusting the respiratory rate and tidal volume to maintain an end-tidal carbon dioxide ($EtCO_2$) level in the 32- to 36-mmHg range. Likewise, if the steep RT positioning causes an increase in peak airway pressures with volume-control ventilation, the ventilation mode is switched to a pressure-control mode. To further optimize surgical exposure and ventilator management, we maintain a deep level of neuromuscular blockade during RLT.

Venovenous bypass

During RLT, total IVC clamping to facilitate the side-to-side cavocavostomy anastomosis is our standard approach.[22] We, therefore, use VVB to maintain hemodynamic stability during this portion of the surgery.

VVB is a technique previously described during LT to mitigate the deleterious effects of full IVC and portal vein cross-clamping. Traditionally, VVB has been used to facilitate venous drainage of the IVC and portal circulation by redirecting of this venous blood through a circuit that includes a bubble trap, heat exchanger, and pump. The blood is then pumped to the IJ or axillary vein for return to the right heart.[47] In this fashion, a VVB system improves hemodynamic stability during the anhepatic phase when a partial IVC clamp cannot be placed. A diagram of our VVB circuit is shown in Fig 5.

Unlike the traditional VVB circuit used for open liver transplantation as described above, with VVB for RLT, blood is drained via a singular femoral venous drainage line without simultaneous drainage of the portal system. The decision to not drain the portal system is based on the anticipated technical challenges and time consumption associated with placing this cannula robotically. For the femoral venous line, a 17Fr cannula is placed by the surgical team as the first step in surgery. The cannula is placed in the surgical field after prepping and draping but before robotic port placement. Blood is then returned to the right IJ via Y-ed 13Fr dialysis catheter that is placed by the anesthesia team.

VVB is initiated during IVC dissection, remains in place during the anhepatic phase, and is weaned off after reperfusion. Goal flows while on VVB are 1.8 to 2.2 liters per minute.[47,48] This flow goal is typically achieved at around 3,200 revolutions per minute via the centrifugal pump. A combination of TEE, CVP, and PPV monitoring is used to guide fluid resuscitation while on VVB. Other visual clues, such as chugging of the VVB lines, indicate the need for ongoing fluid resuscitation. Residual hypotension during VVB after fluid resuscitation is treated with vasopressors.

Anticoagulation strategy

At our institution, the VVB circuit contains a heat exchanger without heparin-coated lines. Therefore, before initiation of VVB, IV heparin is administered for a goal activated clotting time (ACT) of more than 200 seconds. ACT is checked every 30 minutes on VVB. Typically, an initial IV heparin dose of 2,000 units is administered, with subsequent redosing boluses of 1,000 to 2,000 heparin units at 30-minute intervals. After discontinuing VVB, the heparin is reversed with IV protamine. Protamine dosing is calculated based on the most recent ACT value. Typical protamine doses in this setting range from 30 mg to 50 mg. The goal for heparin reversal is to approximate the baseline ACT value.

Transesophageal Echocardiography Imaging

TEE imaging is used during RLT as a routine monitor. We rely on TEE imaging for specific feedback during distinct phases of the LT (Table 2).

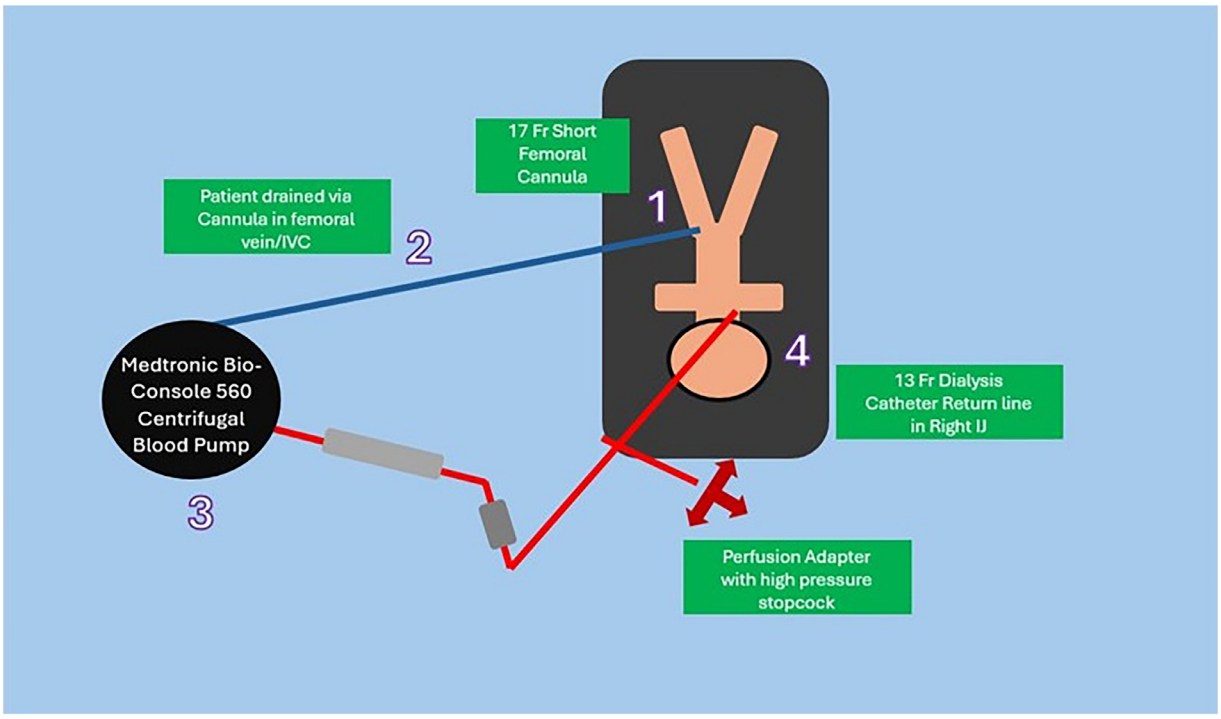

Fig 5. Venovenous bypass machine configuration for robotic orthotopic liver transplantation. A 17Fr femoral venous cannula is used for drainage to the Medtronic Bio-console 560 Centrifugal Blood Pump. Blood is then warmed via a heat exchanger and returns to the patient through a 13Fr right internal jugular dialysis catheter.

VVB cannulation

During placement of the femoral venous cannula by the surgical team for use during VVB, TEE is used to rule out aberrant or unanticipated wire placement. Specifically, TEE is used to confirm wire placement in the intrahepatic IVC before dilation and placement of the large 17Fr cannula.

Table 2
Focused TEE Examination by Phase of RLT

Phase of Surgery	Focused TEE Examination
Venovenous bypass cannulation	Confirm wire placement in intrahepatic IVC before placement of femoral vein cannula. Confirm wire placement in the right atrium before placement of the right internal jugular vein cannula.
Dissection phase	Evaluate for intracardiac air, intracardiac CO_2, and intracardiac thrombi. Evaluate cardiac contractility. Evaluate overall volume status via LVEDV calculation.
Anhepatic phase	Evaluate the adequacy of volume return to the right heart via VVB.
Reperfusion and neohepatic phases	Determine the etiology of postreperfusion syndrome, if applicable. Evaluate right ventricular systolic function to determine if ionotropic support is indicated. Evaluate overall volume status via LVEDV calculation.

Abbreviations: IVC, inferior vena cava; LVEDV, left ventricular end-diastolic volume; TEE, transesophageal echocardiography; RLT, robotic liver transplantation; VVB, venovenous bypass.

Dissection phase

A targeted TEE exam is performed during the dissection phase of RLT to rule out potential causes of hemodynamic or respiratory instability including pericardial effusion, pleural effusion, intracardiac air, intracardiac thrombi, or intracardiac CO_2. CO_2 emboli are of greatest concern during abdominal insufflation and during surgical dissection in close proximity to intrahepatic and perihepatic vascular structures.[49-52] TEE is also used to evaluate cardiac contractility and as a real-time monitor of intracardiac volume status via LVEDV calculation, as described above.[53-56] TEE evidence of decreased left ventricular chamber size would prompt further resuscitation efforts.

Anhepatic phase

The patient is supported on VVB during the anhepatic phase. TEE is used to assess the adequacy of volume return to the right heart through the VVB circuit. Echocardiographic findings of decreased right heart chamber size would prompt increased flow via the VVB circuit and/or further fluid resuscitation.

Reperfusion and Neohepatic Phases

TEE is used to assess for causes of hemodynamic instability associated with postreperfusion syndrome (PRS) during the reperfusion and neohepatic phases.[57,58] While a back-table portal flush is routinely performed during RLT to reduce the incidence and severity of PRS,[59] it is not uncommon for

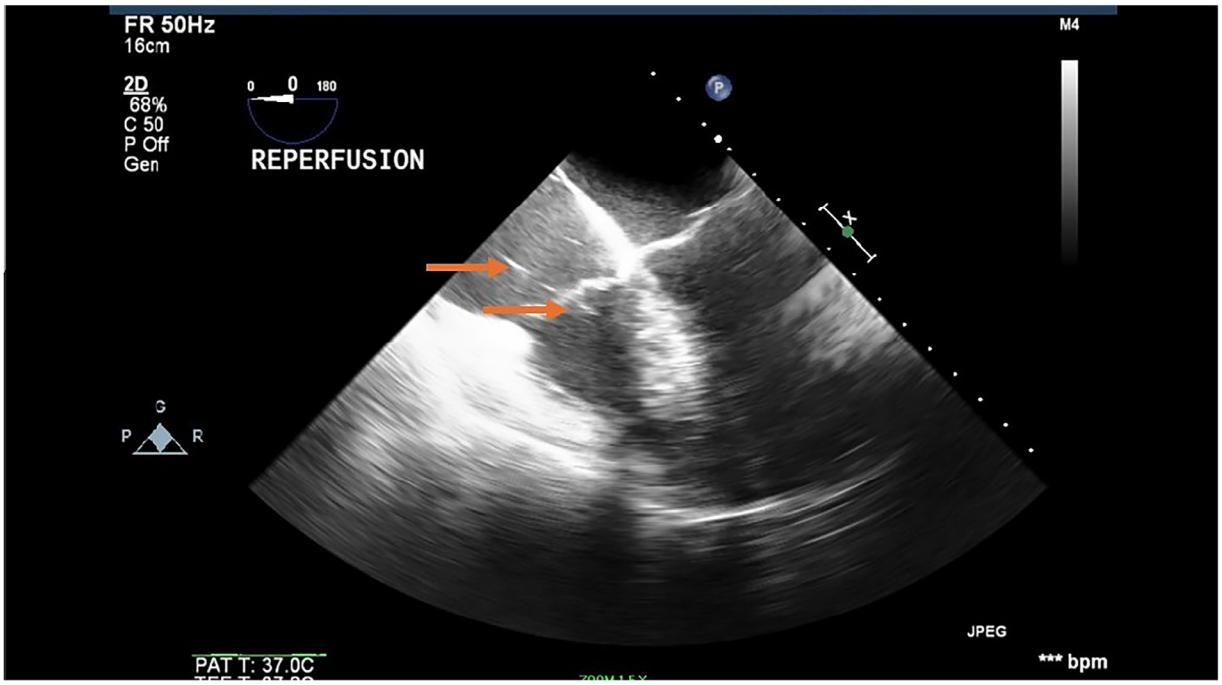

Fig 6. With graft reperfusion, TEE imaging shows evidence of air entrained in the right heart.

residual pockets of air and vasodilatory mediators to be retained in the donor graft and embolize to the heart (Fig 6).[60] The cumulative effect of air, vasodilatory and inflammatory mediators, and hypothermic/acidotic/hyperkalemic blood that is retained in the donor graft and then suddenly enters the recipient heart with reperfusion may result in a myriad of possible untoward physiologic sequelae. Such possibilities include an acute rise in pulmonary artery pressures, acute right ventricular (RV) failure, and arterial vasodilation.[61] Therefore, TEE imaging during this time is used to assess what may be the underlying cause of hemodynamic instability. If RV dysfunction is noted on TEE, inotropic support is initiated. If cardiac function remains robust postreperfusion in the setting of euvolemia, vasopressor support is escalated.

Disposition and Emergence

At the end of surgery, all patients are transferred to the intensive care unit (ICU). If the patient is on a single vasopressor at low or moderate doses, without signs of active bleeding, and on minimal ventilatory support, he or she is extubated in the operating room prior to ICU transfer. If there is concern about ongoing PRS, hemorrhagic shock that requires the use of high-dose or multiple vasopressors, or respiratory failure, the patient remains intubated and is transferred to the ICU with ongoing hemodynamic and ventilatory support.

Challenges in Anesthetic Management

VVB-Related Challenges

As mentioned previously, VVB is used during RLT to maintain venous return from the IVC during caval clamping to minimize hemodynamic instability.[62] However, initiation of VVB induces a variety of pathophysiological sequelae that need to be recognized. VVB has been shown to impair normal perfusion to abdominal organs and lower limbs via a combination of reduced cardiac output, heart rate, and arterial blood pressure.[63] Worsening of hypotension associated with PRS has also been noted with use of VVB, primarily due to VVB-associated upregulation of vasodilatory cytokines such as interleukin-1 and -6.[57,64] An increase in bleeding via hemolysis and platelet depletion has also been shown during VVB, which is primarily mediated via activation of the initial components of the complement system (C3bc) and terminal components of the complement system, along with increases in thrombin-antithrombin complexes, prothrombin fragment, and plasmin–α_2-antiplasmin complexes.[64-66] Overall morbidity and mortality may also increase with VVB use as well.[67-74]

As mentioned previously, we systemically heparinize before and during VVB use at our institution. This heparin-induced coagulopathy that is created during VVB can further augment intraoperative bleeding. Likewise, our VVB circuit utilizes only a singular femoral venous inflow cannula instead of dual inflow from both the femoral and portal veins. The well-described reduction in cardiac output, blood pressure, and CVP associated with dual-inflow VVB use may be further augmented when a singular inflow cannula approach such as this one is used.[63]

Decreased Surgical Exposure and Unrecognized Bleeding

During the anhepatic phase of LT, the hepatic venous, caval, and portal anastomoses are created. Even under the most ideal circumstances, these anastomoses can be technically

challenging, as they require managing size mismatches between the donor and recipient anatomy while minimizing trauma during suturing. After reperfusion, there are further technical challenges related to the biliary anastomoses associated with the need to preserve blood supply to these avascular biliary structures.[75,76]

While robotic liver surgery enhances surgical exposure relative to laparoscopic techniques, there is an added technical challenge associated with completing vascular anastomoses robotically relative to open LT. The transplant surgeons at our institution used cadaver-based simulations to develop the technical skillset needed to complete these robotic-assisted anastomoses. This highlights the value of preexisting expertise and simulation-based preparation to manage robotic operative challenges. [22]

The reduced visual and tactile feedback in robotic surgery may also increase the difficulty of promptly identifying intraoperative bleeding. Abrupt changes to invasive anesthesia monitoring lines such as CVP, beat-to-beat ABP monitoring, PPV, and TEE imaging can provide real-time feedback to aid in the early detection of bleeding. This highlights the importance of vigilance and close monitoring throughout the RLT by the anesthesia team.

Venous Air and Carbon Dioxide Emboli

Venous air emboli (VAE) and CO_2 emboli may be diagnosed intraoperatively based on clinical signs of hypotension, abruptly decreased $EtCO_2$, and hypoxia in the setting of TEE evidence of intracardiac air or CO_2. In most patients undergoing RLT, TEE will show VAE or CO_2 emboli confined to the right heart structures only. However, in the presence of a patent foramen ovale, atrial septal defect, or significant intrapulmonary shunting, air and CO_2 may also be visualized in the left heart.

VAE has been well-described in open LT. In open LT, VAE may occur via two mechanisms: either during venous injury during the dissection phase with translocation of air from the atmosphere to the venous system or via air entrapment in the donor graft that embolizes to the heart during reperfusion.[77,78] While VAE can still occur during RLT from residual air entrapment in the donor graft with reperfusion, unique to RLT when compared to open liver transplantation is the risk of CO_2 embolism. CO_2 is used for abdominal insufflation due to its low flammability and otherwise inert nature, but CO_2 emboli can occur during laparoscopic and robotic surgery with deleterious consequences. When a CO_2 embolism is compared to a VAE, a CO_2 embolism typically causes fewer hemodynamic changes due to the higher solubility of carbon dioxide in the blood relative to air.[79,80] Even if a transient CO_2 embolus does form, its rapid dissolution leads to largely benign clinical manifestations.[81] However, CO_2 emboli can become clinically significant when there is continuous or uninterrupted venous insufflation of CO_2, which can cause diffusion of other gases (primarily oxygen) into the CO_2 embolus with resultant expansion of this air lock.[82,83] Under these circumstances, CO_2 emboli can manifest as RV outflow obstruction and hemodynamic collapse.[84-86]

The two most common causes of CO_2 embolism in laparoscopic or robotic surgery are accidental placement of the Veress needle or insufflating-trocar into a vessel or large venous laceration during surgical dissection.[87] Lower CVP values are associated with higher rates of CO_2 emboli,[87] so the steep RT positioning required during RLT (and the associated low CVP) causes a theoretically increased risk of CO_2 emboli formation. If a vascular injury occurs during surgical dissection under these low-CVP situations, CO_2 can flow down the pressure gradient and embolize to the heart. If a clinically significant CO_2 embolism were to be detected intraoperatively, CO_2 insufflation would be temporarily paused, 100% oxygen would be administered, the patient would be placed in the left lateral decubitus position, and the central venous catheter would be aspirated. [88] The actual incidence of clinically significant CO_2 embolism is likely quite low based on the low incidence reported during minimally invasive major hepatectomy.[89]

Hypothermia

Hypothermia during liver transplantation has been linked to a myriad of poor clinical outcomes, including delayed wound healing, increased incidence of surgical site infections, impaired coagulation, platelet dysfunction, hemorrhage, higher transfusion requirements, and higher risk of cardiac morbidity.[90] As mentioned previously, our strategy for maintaining normothermia includes the utilization of the CWS 5000 warming device (Cocoon, North Geelong, Victoria, Australia) with heat exchanger use on the VVB circuit. Based on our experience, when utilizing both of these warming measures, we can maintain a body temperature greater than 36.0°C throughout RLT.

Emergency Undocking

Emergency undocking during robotic procedures is required for certain life-threatening intraoperative conditions, including cardiopulmonary collapse and uncontrolled hemorrhage.[91,92] Data derived from open LT indicate that LT is one of the highest-risk non-cardiac surgeries.[93] In fact, single-center studies of intraoperative mortality during liver transplantation show the incidence to range from 1 to 5.5%.[93,94] When an arrest does occur, it typically occurs with reperfusion or during the subsequent neohepatic phase due to severe PRS or pulmonary thromboembolism.[94] Therefore, there is a real need for an emergency undocking protocol during every RLT.

Our robotic program has created two distinct emergency undocking protocols that apply to RLT. One protocol is initiated in the setting of uncontrolled surgical bleeding; the other is initiated in the setting of cardiopulmonary arrest. The undocking protocol for uncontrolled surgical bleeding is initiated by the surgeon at the robotic console. This protocol has clearly defined roles and tasks for all team members in the robotic operating room, including the bedside assistant, circulator, scrub tech, and anesthesiologist. The roles of the team members within this protocol are as follows: the console surgeon directs robotic undocking with verbal cues to each team

member, the bedside assistant removes the robotic instruments, the scrub tech detaches the robotic arms, the anesthesiologist resuscitates the patient, the circulator undocks the robot. In contrast, the undocking protocol for cardiopulmonary arrest is initiated by the anesthesiologist but also has clearly defined roles for all team members in the robotic operating room. The roles of the team members within this protocol are as follows: the anesthesiologist directs cardiopulmonary resuscitation efforts, the console surgeon stops operating immediately, the bedside assistant removes the robotic instruments, the scrub tech detaches the robotic arms, and the circulator undocks the robot. Both protocols allow for a coordinated effort among all team members to ensure a safe and efficient undocking of the robotic equipment to facilitate better patient access.

While we do not perform simulation sessions with the anesthesia, surgical, and nursing teams, all members of the robotic transplant team receive extensive education in these emergency undocking protocols before participating in RLT. The emergency undocking protocols are then briefly reviewed during the surgical time-out of RLT, and additional time is made for any team member to ask questions or seek clarification about the emergency protocols. We emphasize team communication during our time-out process, as the Joint Commission lists communication errors as the most common attributable causes of sentinel events in the healthcare setting. [95]

Future Directions

RLT is an innovative operative technique. It offers a minimally invasive approach to an operation that has previously required a large upper-abdominal incision for over 60 years. As increasingly successful RLTs are reported in the medical literature, this new operative technique is gaining momentum within the transplant community as a safe and reproducible approach. We anticipate that with further growth and experience of RLT programs, RLT will be performed with greater regularity, with reduced operating room time, reduced warm ischemia times, and on a broader population with higher MELD scores. Additionally, we anticipate that in the future, VVB will be used on a case-by-case basis instead of as routine care,[22] as evidenced by a recently published case series of six successful deceased donor whole graft RLT without the use of VVB.[23] The emerging field of RLT brings with it a multitude of challenges for the anesthesiologist. We advocate for specific education in RLT and even dedicated robotic anesthesia and nursing teams composed of individuals who understand the nuances of RLT as described above. Recognizing the challenges of RLT and approaching these cases with an in-depth knowledge base of both robotic surgery and liver transplant surgery is critical to ensure optimal patient outcomes.

Declaration of competing interest

Shourik Dutta has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Adeel S. Khan is a proctor for Intuitive Surgical. Chideraa C. Ukeje has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. William C. Chapman is on the Board of Directors of Mid-America Transplant OPO and is an Advisory Board Member for OrganOx Limited. Majella B. Doyle is a proctor for Intuitive Surgical and educator for OrganOx Limited. Meranda Scherer is an educator for Intuitive Surgical. G. Richard Benzinger has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Ivan M. Kangrga has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Jonathan K. Zoller has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Shourik Dutta: Writing – original draft. **Adeel S. Khan:** Writing – review & editing. **Chideraa C. Ukeje:** Writing – original draft. **William C. Chapman:** Writing – review & editing. **Majella B. Doyle:** Writing – review & editing. **Meranda Scherer:** Writing – review & editing. **G. Richard Benzinger:** Writing – review & editing. **Ivan M. Kangrga:** Writing – review & editing. **Jonathan K. Zoller:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

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