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RESEARCH

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Anaesthesiological and perioperative aspects of fully robotic versus open liver transplantation: a matched case–control study

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Abstract

Background Robotic liver transplantation (LT) is a recent advancement in minimally invasive surgery; however, perioperative and anaesthetic management have not yet been described in detail. This study aimed to characterise the anaesthetic course of fully robotic LT and compare the perioperative outcomes with those of propensity score-matched open LT.

Methods We conducted an observational, retrospective, single-centre study at Modena University Hospital. Fully robotic LTs were compared with matched open LTs. Matching was performed in a 1:1 ratio according to age, sex, BMI, year of transplantation, indication, presence of hepatocellular carcinoma, and MELD score.

Results Eighteen robotic and 457 open LTs were initially identified; after matching, 11 robotic and 11 open cases were included in the study. In the robotic group, the operative time was longer ($p < 0.05$) and associated ($p < 0.05$) with higher lactate levels, greater norepinephrine requirement, and larger blood loss, requiring a larger use of blood components compared to standard open surgery. Postoperatively, extubation timing, cardiovascular, respiratory, and liver function recovery, and renal complications were comparable between the groups. Pain control required less opioids ($p < 0.05$) and ICU ($p > 0.05$) and hospital stay ($p < 0.05$) were lower in robotic than in open surgery.

Conclusions Fully robotic LT is associated with longer operative times, greater blood loss, and increased haemodynamic demands. Despite these challenges, postoperative recovery, particularly hospital stay, appears to be favourable. Larger multicentre studies are needed to validate these findings and refine the anaesthetic strategies.

Keywords Liver transplantation, Robotic surgery, Anaesthesia, Perioperative care

Background

Over the past few decades, the utilisation of robotic surgery has expanded to encompass a growing array of surgical procedures, including hepatic surgery. Robotic surgery inherits the advancements of laparoscopy, such as smaller surgical incisions, reduced perioperative stress response, decreased morbidity, and faster recovery times. Additionally, it offers advantages beyond classical laparoscopic surgery, including enhanced visualisation with 3D vision of the surgical field and a greater range of motion.

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In the field of hepatic surgery, a multicentre study involving 398 matched patients who underwent liver resection via open or robotic techniques demonstrated comparable 90-day overall survival rates. However, the robotic approach exhibited significantly shorter hospital stays, fewer ICU admissions, and a lower incidence of post-hepatectomy liver failure [1]. These findings are further supported by a recent meta-analysis comparing robotic versus open liver resection, which highlighted significantly lower overall morbidity, shorter hospital stays, and less intraoperative blood loss in the robotic technique group [2].

Liver transplantation (LT) is the preferred treatment for end-stage organ failure resistant to medical therapy and some unresectable liver cancers, representing one of the most complex abdominal procedures. Advancements in surgical, anaesthesiological, and medical care techniques since the inception of LT have significantly enhanced patient survival rates and outcomes, leading to a notable increase in the number of procedures performed annually. Nevertheless, liver transplantation remains one of the most complex procedures and still carries significant risks of mortality and morbidity [3, 4].

Considering the observed benefits of robotic and laparoscopic techniques in other surgeries compared with open techniques, it is plausible that LT outcomes could similarly improve with the use of robotic approaches. Few cases of fully robotic liver transplantation have been reported thus far although the worldwide interest is rapidly growing [5–9].

This study aimed to describe the anaesthesiological aspects and perioperative data of fully robotic whole graft liver transplantation from a deceased donor and compare them with matched cases of LTs performed using the open technique.

Methods

This observational, retrospective, single-centre, case–control study included patients who underwent fully robotic liver transplantation (LT) and standard open technique LT performed between January 2019 and May 2025. The study was approved by the Institutional Ethics Committee of Area Vasta Emilia Nord (EC AVEN) (215, 2014), and informed consent was obtained from all participants. The study was conducted in accordance with the principles of the Declaration of Helsinki and Good Clinical Practice guidelines. Clinical trial number: not applicable. Patients selected for liver transplantation using the robotic technique were chosen among transplant candidates with preserved hepatic function (Child–Pugh class A or B), a low MELD score, and no severe cardiopulmonary comorbidities. In addition, the initial patients were selected based on anatomical criteria, prioritising those who were non-obese, had a small caudate lobe, and a wide abdominal cavity, while excluding patients with large or bulky livers, such as in polycystic liver disease, and those with portal vein thrombosis. A structured protocol for intra-and postoperative management was applied to all patients (see Supplementary material). In the robotic group, a restrictive fluid strategy was suggested during the pre-anhepatic phase to minimise caval engorgement and reduce blood loss during hepatectomy. From the anhepatic phase onwards, a more liberal fluid strategy is suggested to maintain normovolaemia. Norepinephrine was used to achieve and maintain a mean arterial pressure between 50 and 70 mmHg. A pulmonary artery catheter with a continuous thermodilution system was used to measure the cardiac output in all patients. A mini-laparotomy, utilising an 11 cm median or Pfannenstiel incision, was employed to retrieve the native liver following the hepatectomy and to facilitate the insertion of the graft for implantation. Subsequently, the access site was closed with a gelport, and the anastomoses were constructed using robotic techniques. A side-to-side cavo-caval anastomosis with preservation of the recipient inferior vena cava was performed in all the cases.

Patients in the robotic and open surgery groups were matched 1:1 using a propensity score with the nearest-neighbour method based on age, sex, body mass index (BMI), year of transplantation, indication for transplantation, presence of hepatocellular carcinoma (HCC), and Model for End-Stage Liver Disease (MELD) score.

Continuous and categorical variables were compared using Mann–Whitney and chi-square tests when appropriate, and p-values < 0,05 were considered significant (SPSS, version 20.0; IBM Corp., Armonk, NY, USA).

Results

The initial study population included 18 fully robotic and 457 open LTs cases. After matching, 11 fully robotic and 11 matched open cases were analysed. The two groups were well balanced in terms of age, sex, anthropometric characteristics, year of transplantation, indication for LT, MELD score, and Child score (Table 1).

Intraoperative

The total intraoperative time and the duration of the anhepatic phase were longer ($p < 0.05$) in the robotic group than in the standard open group (Table 2). Although a smaller rate of crystalloids infusion ($p < 0.05$), the fluid rate (including blood components) during surgery was similar between the 2 groups resulting in a larger ($p > 0.05$) amount of fluid administered in the robotic group. This group experienced greater blood loss ($p < 0.05$) and larger amounts of red blood cells,

Table 1 Main characteristics of patients subdivided into fully robotic and standard open surgery groups

			Robotic ($n=11$)		Open ($n=11$)		p
Age		Years (mean; SD)	65	5	65	4	*ns*
Sex		Male (*n*;%)	9	81,8%	9	81,8%	*ns*
Weight		Kg (mean; SD)	80	11	78	10	*ns*
Body Mass Index		Kg/m^2 (mean; SD)	26,7	3,7	26,8	3,8	*ns*
Year of LT	2023	(*n*;%)	0	0%	1	*ns*	
	2024		5	45,5%	5	45,5%	
	2025		6	54,5%	5	45,5%	
Cause of LT	Viral	(*n*;%)	2	18,2%	2	18,2%	*ns*
	Dysmetabolic		8	72,7%	7	63,6%	
	Viral and dysmetabolic		1	9,1%	2	18,2%	
Hepatocarcinoma		(*n*;%)	9	81,8%	10	90,6%	*ns*
Child–Pugh score	A	(*n*;%)	9	81,8%	11	100%	*ns*
	B	(*n*;%)	2	18,2%	0	0%	
MELD score		Points (mean; SD)	11,14	5,10	9,85	1,86	*ns*

LT liver transplantation, *MELD* Mayo End stage Liver Disease

fibrinogen ($p<0.05$), and fresh frozen plasma ($p<0.05$) infusions. A larger total fluid balance was observed in the robotic cases than in the open cases ($p<0.05$). In the robotic group, central venous pressure and pulmonary artery occlusion pressure tended to be lower, particularly in the early stages of transplantation (Fig. 1). Norepinephrine was more frequently used ($n=10$) with higher doses in robotic than in open recipients ($n=7$). Three patients in the robotic and two in the open-surgery groups developed reperfusion syndrome [10]. In the robotic surgery group, lower pH and bicarbonate levels and higher serum lactate levels were observed at all stages of the surgical procedure than those in the open surgery group.

Post-operative

After surgery, all patients were transferred to the ICU and extubated at comparable times between the robotic and standard groups; none required reintubation or further mechanical ventilation (Table 3). At the end of surgery and in the first 12 h after ICU admission, the PaO_2/FiO_2 ratio was lower in the robotic group than in the open group. Patients undergoing robotic and open liver transplantation required norepinephrine support for similar durations and at comparable doses during their intensive care unit stay. Blood lactate levels decreased at the same rate in both groups, with the 2 mM threshold achieved later in the robotic than in the standard open group. Liver function recovery was comparable between the groups. In the robotic group, three patients developed mild postoperative renal impairment (AKI stage 1 according to the KDIGO criteria [11], which resolved during the postoperative course, whereas in the open group, two patients developed more severe AKI (KDIGO stages 2 and 3). Patients in the robotic LT group required significantly less morphine ($p<0.05$) and were discharged from the ICU ($p>0.05$) and the hospital ($p<0.05$) quicker than patients undergoing standard technique.

Discussion

Our preliminary experience indicated that robotic LT was associated with longer operative times, greater blood loss, increased intraoperative fluid and vasopressor demands, and higher lactate levels than open LT. Despite these intraoperative challenges, postoperative recovery, particularly hospital stay and liver function recovery, appeared to be favourable in the robotic group. To our knowledge, this is the first comparative study to report the anaesthetic and perioperative aspects of fully robotic LT [12, 13].

According to previous data on hepatic surgery, robotic LT is associated with longer operative times [14, 15]. This may be explained by the technical complexity of robotic LT and the learning curve associated with its implementation. The same rationale may also account for the increased intraoperative blood loss observed compared with open procedures, leading to a heightened demand for blood product transfusions. Another propensity-matched study reported a similar increase in estimated blood loss during robotic liver resection compared with the open approach [1]. Nevertheless, the majority of published literature showed lower blood loss associated with robotic technique [6, 16–18]. Most bleeding events in the robotic liver transplantation cohort occurred gradually during the surgery. Only one patient experienced an acute bleeding event. The higher intraoperative blood loss observed in the robotic cohort may be partially

Table 2 Intraoperative time, physiological variables, and treatments in fully robotic and standard open surgery

		Robotic LTs		Open LTs		*p*
		Mean	SD	Mean	SD	
Intraoperative time	min	654	103	344	64	< 0.05
Anhepathic phase length	min	73	15	35	5	< 0.05
Crystalloids infusion	ml	8505	2427	6125	1992	< 0.05
Crystalloids infusion rate	ml/h	689.2	132.3	817.4	252.6	ns
Colloids infusion	ml	1061	801	589	362	ns
Colloids infusion rate	ml/h	88.4	61.6	75.3	46.0	ns
Blood losses	ml	1618	1213	423	88	< 0.05
Red blood cells transfused	ml	668	1009	51	169	ns
Fresh frozen plasma transfused	ml	545	593	64	211	< 0.05
Total infused fluids	ml	11.054	3654	6926	2086	< 0.05
Total fluids infusion rate	ml/h	892.3	223.0	923.2	253.4	ns
Fibrinogen transfused	g	3.0	2.7	0.7	1.6	< 0.05
Intraoperatory diuresis rate	ml/kg/h	1.60	0.79	2.04	1.18	ns
Total intraoperatory diuresis	ml	1549.1	561.9	1070.9	416.6	< 0.05
Total Intraoperatory fluid balance	ml	5163.8	2618.9	2020.6	1209.5	< 0.05
Norepinephrine pre-anhepatic phase	% time	30%	29%	15%	24%	ns
Norepinephrine pre-anhepatic phase	mcg/kg/min	0.10	0.09	0.03	.06	ns
Norepinephrine anhepatic phase	% time	86%	30%	36%	50%	< 0.05
Norepinephrine anhepatic phase	mcg/kg/min	0.25	0.24	0.04	0.06	< 0.05
Norepinephrine neo-hepatic phase	% time	80%	37%	35%	40%	ns
Norepinephrine neo-hepatic phase	mcg/kg/min	0.22	0.20	0.05	0.05	< 0.05
MPAP pre-anhepatic phase	mmHg	13	4	19	1	< 0.05
MPAP anhepatic phase	mmHg	10	3	13	2	ns
MPAP neo-hepatic phase	mmHg	16	4	18	3	ns
SVI pre-anhepatic phase	ml/m2	46	15	47	21	ns
SVI anhepatic phase	ml/m2	33	16	22	3	ns
SVI neo-hepatic phase	ml/m2	50	22	51	4	ns
pH pre-anhepatic phase	U	7.38	0.08	7.41	0.03	ns
pH anhepatic phase	U	7.30	0.09	7.37	0.04	< 0.05
pH neo-hepatic phase	U	7.29	0.05	7.32	0.04	ns
HCO3 pre-anhepatic phase	mMol/L	22.4	1.71	24.2	1.47	< 0.05
HCO3 anhepatic phase	mMol/L	18.7	2.87	20.94	1.95	< 0.05
HCO3 neo-hepatic phase	mMol/L	18.08	3.20	21.32	1.09	< 0.05

attributed to two factors: the surgeons' learning curve during the initial phase of adopting this novel technique and metabolic acidosis, frequently observed in the perioperative period, which may have impaired coagulation. Moreover, it is crucial to consider that, as indicated by another study from our group, there is an inherent bias in the assessment of estimated blood loss during minimally invasive surgery [1]. Compared to open surgery, the estimation of blood loss is more accurate due to the closed system employed, which does not utilise large gauzes or cell savers that could compromise the precision of blood loss estimation. This factor may partially account for the differences observed between the robotic and open surgery groups in our study. Further studies involving larger patient cohorts are required to clarify the actual risk of bleeding associated with the use of the robotic technique.

The increased requirement for vasopressor support in the robotic group during the anhepatic and neohepatic phases can be attributed to several factors. Firstly, in comparison to open surgery, the positioning of the patient and the use of pneumoperitoneum may reduce venous return, thereby necessitating the use of vasopressors to maintain adequate perfusion pressure. Additionally, acidosis may have further exacerbated these hemodynamic alterations. Consequently, although the

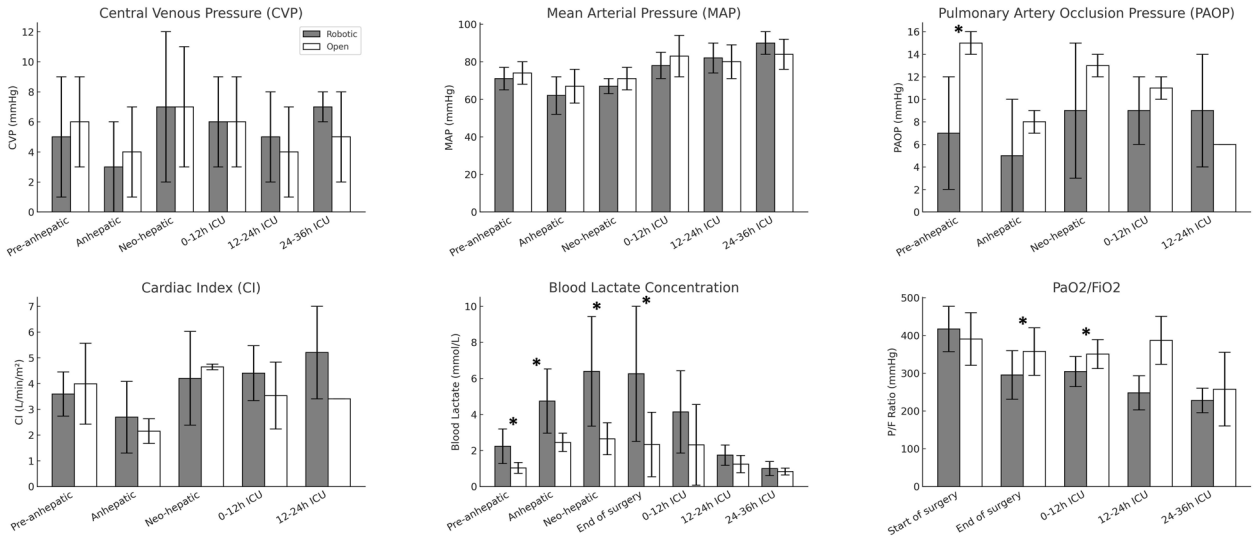

Fig. 1 Mean and SD for cardiovascular and respiratory parameters. Bars: mean values; whiskers: standard deviation. Grey bars: robotic cases; White bars laparotomic controls. **p*-value < 0.05. MAP: mean arterial pressure; CVP: central venous pressure; PAOP: pulmonary artery occlusion pressure; CI: cardiac index; PaO2/FiO2: Arterial oxygen partial pressure/inspired oxygen fraction; 0–12 h ICU: from ICU admission to 12 h after ICU admission; 12–24 h ICU: from 12 to 24 h after ICU admission; 24–36 h ICU: from 24 to 36 h after ICU admission

Table 3 Postoperative time, physiological variable, and treatments in fully robotic and standard open surgery

		Robotic ($n=11$)		Open ($n=11$)		*p*
		Mean	**SD**	**Mean**	**SD**	
Time from ICU admission to serum lactates ≤ 2 mMol/L	hours	13.59	10.49	4.23	7.24	< 0.05
Norepinephrine during ICU stay	hours	1.63	2.83	0.98	2.81	< 0.05
Norepinephrine during ICU stay	mcg/kg/min	0.04	0.06	0.02	0.06	< 0.05
Time to extubation	hours	7.45	4.46	8.18	9.25	ns
Worst PaO2/FiO2 extubation	mMol/L	233.36	63.14	274.55	79.14	ns
Worst serum creatinine during ICU stay	mg/dl	1.06	0.31	1.58	1.36	ns
Maximum creatinine increase from baseline during ICU stay	%	1.10	0.54	1.32	0.86	ns
Worst bilirubin during ICU stay	mg/dl	3.7	2.7	2.9	1.3	ns
Worst GOT during ICU stay	U/L	1310	964	1443	1547	ns
Worst GPT during ICU stay	U/L	943	693	763	702	ns
Worst INR during ICU stay		2.02	0.37	1.91	0.36	ns
Morphine requirement	mg/24 h	4.6	4.2	8.6	4.7	< 0.05
SVI during ICU stay	ml/m2	61	14	67	37	ns
SVRI during ICU stay	dyne*s*cm5*m2	1592	543	1843	980	ns
pH during 0–12 h in ICU		7.39	0.05	7.35	0.03	< 0.05
pH during 12–24 h in ICU		7.44	0.05	7.40	0.05	ns
pH during 24–26 h in ICU		7.49	0.07	7.42	0.04	ns
ICU length of stay	hours	27.2	13.2	50.9	36.5	ns
Hospital length of stay	days	6	1	12	5	< 0.05

restrictive fluid strategy was abandoned during the anhepatic and neohepatic phases, higher vasopressor doses were still required to preserve adequate perfusion while avoiding fluid overload.

Patients in the robotic transplant group exhibited higher intraoperative lactate levels, probably reflecting, among other factors, the increased need for vasopressor support during surgery. Despite these intraoperative

challenges, early postoperative recovery of liver function was similar in both groups, and no major differences were observed in renal function outcomes. Robotic LT was associated with a trend toward shorter ICU stays and a significantly reduced hospital length of stay compared with the standard open technique. These findings are consistent with the advantages of robotic surgery reported in other hepatic and abdominal procedures, suggesting that increased perioperative complexity may be offset by faster postoperative recovery and fewer complications. A similar reduction in ICU and hospital stay has been described in a few published reports on fully robotic liver transplantation, all of which involved living donor LT [6, 19]. Furthermore, the largest study on fully robotic liver transplantation also reported lower rates of overall complications and infection, together with improved recipient survival [6].

Our study had several limitations. The small sample size, inherent to the novelty of robotic LT, reduces the statistical power of our comparisons and may obscure differences in rare but clinically relevant outcome measures. Moreover, this was a single-centre, retrospective study, which may limit generalisability and remains subject to selection bias despite propensity score matching. Finally, the learning curve for both surgeons and anaesthesiologists must be acknowledged, as outcomes may evolve with greater institutional experience.

Conclusion

This study highlights the feasibility of robotic LT from an anaesthetic and perioperative standpoint while acknowledging the unique challenges it presents compared with the open technique. As this technique continues to evolve, accumulating experience and multicentre studies will be crucial to validate these findings, refine anaesthetic strategies, and clarify the balance between intraoperative complexity and postoperative benefits.

Abbreviations

LT	Liver transplantation
ICU	Intensive care unit
BMI	Body mass index
HCC	Hepatocellular carcinoma
MELD	Model for end-stage liver disease
MAP	Mean arterial pressure
MPAP	Mean pulmonary artery pressure
CVP	Central venous pressure
PAOP	Pulmonary artery occlusion pressure
CI	Cardiac Index
SVI	Stroke Volume Index
SVRI	Systemic Vascular Resistance Index
PaO_2/FiO_2 ratio (P/F ratio)	Arterial oxygen partial pressure/fraction of inspired oxygen ratio
AKI	Acute kidney injury
KDIGO	Kidney Disease: Improving Global Outcomes
SD	Standard deviation
Ns	Not significant

Supplementary Information

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Supplementary Material 1.

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Authors' contributions

GM and TM conceived the study; RE and TM collected data from the clinical charts and compiled the dataset. TM analysed and interpreted the patient data and drafted the manuscript. GE, BE, BS, MP and DBF critically revised the manuscript; BF, GC SDJ and TM performed anesthesias and contributed to clinical data acquisition; MP, GPG, DSS and DBF performed surgeries and contributed to clinical data acquisition. All the authors have read and approved the final manuscript.

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Data availability

The datasets used and analysed in the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

The study was approved by the Institutional Ethics Committee of Area Vasta Emilia Nord (EC AVEN) ($n=215$, 8 July 2014), and informed consent was obtained from all participants.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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