transplantology

Review

Robotic Surgical Techniques in Transplantation: A Comprehensive Review

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Abstract: In the field of surgery, the idea of performing organ transplants in a minimally invasive fashion has always been a significant technical challenge. The advent of the robotic approach facilitated the overcoming of difficulties in highly complex surgical procedures that demand high technical skill. Furthermore, robotic transplants are showing significant benefits in patient outcomes, particularly in the obese population. The purpose of this review is to provide an overview of the current state of robotics applications for transplant surgery. Kidney transplants were the first to be performed using a fully robotic approach. Since then, robotic surgery has gradually been applied to other organ transplants, with very recent reports of fully robotic lung and liver transplants. Further experiences and studies will be needed to verify their effectiveness and to satisfy some concerns regarding the longer warm ischemia time related to the robotic approach in comparison with open surgery.

Keywords: robotic transplant; robotic kidney transplant; robotic pancreas transplant; robotic liver transplant; robotic lung transplant; minimally invasive transplant

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Citation: Di Pangrazio, M.; Pinto, F.; Martinino, A.; Toti, F.; Pozza, G.; Giovinazzo, F. Robotic Surgical Techniques in Transplantation: A Comprehensive Review. *Transplantology* **2024**, *5*, 72–84. https://doi.org/10.3390/transplantology5020008

Academic Editor: Nobuhisa Akamatsu

Received: 6 December 2023
Revised: 1 March 2024
Accepted: 22 April 2024
Published: 25 April 2024

1. Robotic Transplant Surgery: Current Status

Robot-assisted surgery (RAS) is a ground-breaking field that is redrawing the boundaries of surgery, allowing for smaller incisions, minimizing blood loss, hastening recovery times, and improving patient outcomes. From delicate surgeries to complex procedures, robots are now playing a pivotal role in assisting surgeons across various specialties.

The application of robotics is rapidly increasing in transplant surgery, a field in which the demand for accuracy, precision, and effectiveness is bigger than in any other. Despite the concern about the ischemic time, the complexity of the surgical gesture, and the high level of training, robotic transplants are giving successful results, especially in obese patients [1,2].

The very first robotic transplant was performed by Giulianotti and colleagues in 2009, and it was a hand-assisted robotic kidney transplant in an obese patient [3]. Since this milestone, the robotic platform has notably made significant strides, particularly in the field of kidney transplantation, where its contributions and utilization have expanded substantially [4]. In the following years, the use of robotics was also applied to liver transplants, pancreas transplantations, and simultaneous pancreas–kidney transplantation (SPK). Most recently, the first cases of robotic-assisted single lung transplantation and fully robotic liver transplantation have been published.

This review aims to provide an overview of the current applications of robotic technology to the transplant field, according to the most recent published reports. Due to the distinct magnitude associated with various surgical techniques, every specific organ transplant will be discussed separately.

2. Robotic-Assisted Kidney Transplant (RAKT)

The first application of robotics to a kidney transplant dates back to 2001 when Hoznek et al. reported a hybrid technique using the DaVinci System by Intuitive Surgical Inc. (Sunnyvale, CA, USA). The procedure involved the alternation of three steps: first, the bedside surgeon established the abdominal access through an open incision in the iliac fossa; after that, the console surgeon performed the dissection phase and the vascular anastomosis; finally, the assistant surgeon again accomplished the ureteric anastomosis [5]. In the same period (2002), Horgan et al. described their first series of 12 robotic left donor nephrectomy, using a combination of a robotic camera and standard laparoscopic instruments. They recorded no intraprocedural complications, no conversions, and no mortalities. The operative and warm ischemic times were considerably longer than the open approach, but this did not affect short-term graft function. Furthermore, the technique showed lower donor morbidity [6].

A few years later (2009), as mentioned before, Giulianotti and colleagues performed the first hand-assisted robotic kidney transplant in an obese patient (BMI 41 kg/m^2), with a history of caesarean section and bilateral ureteral reimplantation when she was 5 years old. The graft was delivered through a periumbilical incision of 7 cm, for a transperitoneal approach. A device for hand assistance (Lap Disc, Ethicon, Cincinnati, OH, USA) was inserted. The hand assistance was intended to manipulate the graft intracorporeally. The ureteric anastomosis, robotically performed, required the re-docking of the DaVinci Si. The operative time was 223 min with 55 min of warm ischemia. The graft was immediately functioning, and the patient was discharged on postoperative day 5. The serum level of creatinine decreased from 4.9 mg/dL before transplantation to 1.3 mg/dL on the discharge day. The advantage of the small periumbilical incision was intended to decrease the risk of eviscerations and surgical site infections (SSI), both more frequent in obese patients. This first case emphasized in advance one of the greatest benefits of robotic surgery: its application to obese people, expanding the limits of the transplant surgery further than the traditional open technique [3].

In 2010, Boggi et al. reported their experience of hand-assisted RAKT using a Pfannenstiel access of 7 cm, on the same site of a previous suprapubic incision for hysterectomy. The uretero-vesical anastomosis was performed using a standard open technique through the suprapubic incision. The procedural approach was initially transperitoneal, even though finally the graft was placed extraperitoneally. The total operative time was 154 min, while the warm ischemia time was 51 min. The postoperative course was uneventful. Urine production started immediately, and no anastomosis leakage was noted [7].

In early 2013, Oberholzer and colleagues published the initial series involving 39 obese patients who underwent RAKT between June 2009 and December 2011 at the Department of Surgery, University of Illinois at Chicago. The procedure followed the technique previously described by Giulianotti [3]. To comprehensively assess the advantages of the robotic approach, Oberholzer et al. compared the outcomes of patients with at least six months of follow-up to a frequency-matched retrospective cohort of 28 obese patients who received an open kidney transplant from 2004–2009 at the same Institution. The robotic group had a BMI of 42.6 ± 7.8 kg/m^2, whereas the control group had a BMI of 38.1 ± 5.4 kg/m^2 ($p = 0.02$). No surgical site infections (SSI) occurred in the robotic group (0/28), while 28.6% (8/28) of the control group developed an infection ($p = 0.004$). Six-month creatinine levels (1.5 ± 0.4 vs. 1.6 ± 0.6 mg/dL; $p = 0.47$) and patient and graft survival (100%) were comparable between the two groups. The outcomes of robotic surgery demonstrated a favorable comparison to conventional transplantation [8].

In 2013, Menon et al. described the first fully RAKT. It was a prospective study of 50 consecutive patients with end-stage renal disease (ESRD) who underwent living-donor fully RAKT with regional hypothermia given by an ice slush solution to maintain pelvic temperature at 18–20 °C. A periumbilical incision was chosen for the GelPOINT placement (Applied Medical Resources Corp, Rancho Santa Margarita, CA, USA). The graft was anastomosed with a transperitoneal approach, to be moved into its definitive retroperitoneal position at the end of the surgery. The ureteric anastomosis was performed robotically with no need for re-docking. There was no evidence of anastomotic problems requiring reoperations and no need for conversion to an open approach. The average operative time was 214 min, with a medium rewarming time of 47 min. The time required for the anastomosis was 12 min for the artery and 13 min for the vein. No cases of delayed graft function requiring postoperative dialysis were observed. No patient developed anastomotic leaks or wound complications. There was one case of immediate re-exploration after the skin-closure due to poor blood flow on Doppler ultrasound and the absence of urine production. This issue was identified as resulting from vessel kinking during the retroperitonealization of the graft [9].

In 2014, Tsai and colleagues documented their series of 10 patients who received RAKT with a totally retroperitoneal approach. This technique involved a Gibson incision, typically made in the right iliac fossa. However, it is worth noting that two patients deviated from this norm: one had a temporary dialysis catheter in the right femoral vein, while the other had a peritoneal catheter on the right side. In both cases, the renal graft was placed on the left side. It is important to mention that ureteric anastomosis was not performed robotically, and there were no reported complications related to anastomosis or wound healing. One patient experienced delayed graft function, likely due to prolonged warm ischemia during donor nephrectomy due to stapler malfunctioning. This patient required peritoneal dialysis for 7 days post-transplant and was discharged on postoperative day 20 [10].

In 2015, the French group led by Doumerc et al. reported the first case of living donor RAKT using an innovative transvaginal approach for both donor and recipient surgeries. This approach leveraged natural orifices to access and position the kidney effectively. The operative time for the transplant was 200 min, and the time for the vascular anastomosis was 55 min. No pre- or postoperative complications occurred. The patient was discharged on postoperative day 10 with a regular Doppler ultrasound of the renal vessels and normal kidney function [11].

In 2021, Musquera and colleagues published their prospective analysis of the first five cases of robotic kidney transplantation with a transvaginal access, using an Alexis retractor. No procedural complications or need for conversion to an open approach were recorded. Both the uretero-vesical anastomosis and the vagina closure were performed robotically. At the end of the surgery, the kidney was positioned extra-peritoneally. The median operative time was 220 min, while the mean rewarming ischemia time was 53 min. The diuresis was immediate. There were no intraoperative complications. The mean hospitalization period was 9 days, with a mean level of serum creatinine of 1.5 mg/dL at discharge [12].

In 2015, Sood et al. documented their series comprising 67 consecutive end-stage renal disease (ESRD) patients who underwent RAKT at a single institution between January 2013 and June 2014, following the technique described by Menon. Notably, no instances necessitating conversion to open surgery were observed (0%). The mean console, warm ischemia, and rewarming times were 130.8 min, 2.3 min, and 42.9 min, respectively. Extraperitonealization of the graft insured against graft torsion (0%). There were no cases of vascular thromboses, strictures, or leaks (0%) [13].

In 2017, Breda and colleagues published the European experience: a multicenter prospective observational experience of 120 patients who received an RAKT in eight European institutions from July 2015 to May 2017. The robot-assisted surgical steps were transperitoneal dissection of the external iliac vessels, venous/arterial anastomosis, graft retroperitonealization, and ureterovesical anastomosis. The median operative time was 250 min, and the vascular suture time was 38 min. The median EBL was 150 mL. No major intraoperative complications were observed. However, two patients required open conversion due to low blood flow detected by Doppler ultrasound immediately after skin closure, resulting in the longest operative times. Both early and late graft function had no correlation to overall operating time or rewarming time. Five cases of delayed graft function (4.2%) occurred. There was one case (0.8%) of wound infection, three cases (2.5%) of ileus, and four cases of bleeding managed conservatively (3.3%; three of them required blood transfusion). One case (0.8%) of deep venous thrombosis, one case (0.8%) of lymphocele, and three cases (2.5%) of transplantectomy due to massive arterial thrombosis were recorded. Surgical exploration was performed in five cases (4.2%) for intraperitoneal hematoma [14].

In 2020, Tzvetanov and colleagues published their 10 years of experience: a single-center retrospective analysis of RAKT cohorts from January 2009 to December 2018. Two hundred and forty-eight patients were included in the study. The conversion rate was 3.9% (9 cases), with 239 RAKTs successfully performed. Conversion was mainly due to poor kidney reperfusion requiring reimplantation (6 cases), venous bleeding difficult to control, and iliac artery reconstruction for dissection. The median BMI was 41.4 kg/m^2. In 19 cases, the patients underwent already a prior kidney transplant. The median operative time was 4.8 h, and the warm ischemia time was 45 min. Wound complications (mostly seromas and hematomas) occurred in 3.8% of patients, with one patient developing an SSI. Reoperation within 30 days from transplant included ureter reimplantation for urinary leak (6 cases), artery bleeding (1 case), and two cases of graft nephrectomy (for hyperacute rejection and vascular thrombosis). One patient who received a simultaneous pancreas–kidney transplant required a laparoscopic washout for pancreatitis. One patient had a partial small bowel obstruction due to a trocar site hernia, which was reduced and repaired laparoscopically [4].

Hence, data from the last two decades show a larger and larger application of robotic technology in kidney transplantations, with positive and promising results. Since the very first case, different surgical techniques have been described. At the very beginning, the robotic platforms were used mostly for dissection and vascular anastomosis, leaving the ureter implantation to the traditional open approach. The comparison between the intraperitoneal and the extraperitoneal location of the graft showed advantages and disadvantages for both sides. The intraperitoneal approach allows more room during the surgical procedure, which is essential for vascular anastomosis. But in this case, the graft mobility could lead more easily to vessel torsion. On the other hand, the extraperitoneal fixation of the graft decreases the risk of vascular torsion but also reduces the robotic working space. Additionally, with an extraperitoneal location, performing necessary biopsies for rejection is simplified, yet it heightens the risk of surgical site infection (SSI). Some authors have explored the transvaginal approach, although this technique is approached cautiously in transplantation.

The Breda multicenter experience underscored the critical role of engaging trained, skilled, and experienced surgeons to navigate the intricacies and potential complications of RAKTs. However, despite its complexity, RAKT continues to demonstrate widespread applicability across various centers, consistently yielding excellent outcomes [14].

It is in the obese patient population that RAKT achieved the most satisfying results, especially when compared to the traditional open technique. Patients with obesity have limited access to kidney transplantation, primarily due to higher incidence of surgical complications such as SSI, ventral hernias, intra-abdominal infections, graft loss, and mortality [15]. The selective use of robotic-assisted surgery has the potential to reduce these complications. Lynch et al. showed, in kidney transplant recipients, that SSIs are associated with a significant risk of premature graft loss and a tendency toward lower patient survival. Additionally, they found that a BMI above 30 is a risk factor for wound infection (23.7% in the obese group versus 10.5% in the non-obese group) and fascial dehiscence (4.2% in the obese group versus 1.1% in the non-obese group) [16]. The adoption of robotic surgery may offer obese patients with end-stage renal disease (ESRD) increased access to kidney transplantation, potentially mitigating health disparities in populations with a high prevalence of obesity and ESRD.

Many transplant centers implement interventions to address obesity in kidney transplant candidates, providing dietary education and encouraging lifestyle modifications. In cases where nutritional restriction and medical therapy prove ineffective, the consideration of bariatric surgery may enhance the transplant candidacy of patients with both obesity and ESRD [17]. Moreover, it holds the potential to improve both immediate and long-term outcomes. For non-obese patients, there are data indicating comparable outcomes between open surgery and robotic surgery [18]. Consequently, we think physicians should opt for open surgical procedures when performing kidney transplants in non-obese individuals. The optimal timing of bariatric surgery and the most suitable surgical approach are still under investigation. Nevertheless, pretransplant laparoscopic sleeve gastrectomy (LSG) appears to be linked to an acceptable risk–benefit profile.

In 2020, Spaggiari and colleagues reported a prospective randomized controlled trial, comparing the safety and efficacy of combining robotic sleeve gastrectomy and RAKT to robotic kidney transplant alone in candidates with class II or III obesity. A total of 20 candidates were enrolled, with 11 randomized to the robotic sleeve gastrectomy and RAKT group, and 9 to the robotic kidney transplant group. At the 12-month follow-up, there was a significant change in body mass index, with a decrease of -8.76 ± 1.82 in the robotic sleeve gastrectomy and RAKT group compared to an increase of 1.70 ± 2.30 in the robotic kidney transplant group ($p = 0.0041$). However, estimated glomerular filtration rate, serum creatinine, readmission rates, and graft failure rates up to 12 months did not differ between the two groups. The length of surgery was longer in the robotic sleeve gastrectomy and RAKT group (405 min vs. 269 min, $p = 0.00304$), but this was not associated with an increase in EBL (120 mL vs. 117 mL, $p = 0.908$) or incidence of surgical complications. Overall, combined RAKT and sleeve gastrectomy was shown to be safe and effective compared to RAKT alone [15].

Achieving positive technical results in terms of Renal Warm Ischemia Time (RWT) during RAKT typically requires experienced surgeons to complete approximately 35 cases. Establishing synergy between the surgeon and the assistant is crucial for minimizing the time between vascular anastomoses. To mitigate complications during early RAKTs, the recommendation is to prioritize hands-on training and proctorship [19].

A Systematic Review and Meta-analysis (SRMA) conducted by Slagter et al. [20] compared RAKT and Open Kidney Transplant (OKT) to compare the two surgical approaches in terms of peri-operative outcomes, early postoperative outcomes, and long-term renal function. In their meta-analysis, the authors observed lower relative risks (RRs) for the development of surgical site infections (SSI), symptomatic lymphocele, shorter hospital stays, decreased postoperative pain, and a smaller incision length when comparing RAKT with OKT. Notably, no significant differences were found in long-term renal function, graft survival, and patient survival between the two approaches. The study also highlighted that RAKT is an excellent technique for preventing the occurrence of surgical site infections (SSIs), even in the obese population. Consequently, in the absence of contraindications, RAKT could be considered the preferred surgical technique for kidney transplant recipients who are obese. However, the authors emphasize the need for more comparative research in this population, preferably through well-powered randomized controlled trials (RCTs) to provide more robust evidence and further validate these findings.

In their thorough examination of the robotic technique compared to the laparoscopic approach, Hinojosa-Gonzalez et al. [21] conducted an extensive Systematic Review and Meta-analysis (SRMA) to systematically scrutinize the perioperative outcomes associated with these two surgical methods. The authors noted a non-significant difference in EBL between the two approaches. Moreover, they observed longer warm ischemia times in the robotic surgeries. An intriguing finding emerged as patients undergoing robotic surgeries experienced decreased hospitalization time and postoperative pain when measured using a Visual Analog Scale (VAS). Upon further analysis of complication rates and conversion rates, the authors identified similar outcomes between the two techniques.

In a retrospective analysis of surgical outcomes from two high-volume European centers [22], a comparable rate of postoperative complications was observed between the two groups. However, patients undergoing robotic nephrectomy exhibited longer operative times and warm ischemia times. Interestingly, the authors reported a higher rate of intraoperative complications in the robotic group but noted a shorter hospitalization period for this cohort.

In conclusion, despite the prolonged operative times and extended ischemic periods associated with RAKT, the literature indicates comparable patient and graft survival rates between the robotic and open surgery groups. Initial higher serum creatinine levels in the postoperative days seem to be a correlated factor, but ultimately, discharge serum creatinine levels show similarity in both groups.

Table 1 presents the outcomes of these studies.

Table 1. Peri-operative outcomes in RAKT; ACR: acute cellular rejection; SPK: simultaneous pancreas–kidney; KT: kidney transplant; SG: sleeve gastrectomy.

Authors	N° of Patients	Length of Procedure	Warm Ischemia Time	Complications	Patient Survival	Graft Survival
Giulianotti et al. (2009) [3]	1 RAKT	223 min	55 min	/	/	/
Boggi et al. (2010) [7]	1 RAKT	154 min	51 min	/	/	/
Oberholzer et al. (2013) [8]	28 RAKT 28 Controls	Not reported	47.7 min	7 patients (25%) in the robotic group underwent kidney biopsy for rejection suspicion. Rejection occurred in 7 (25%) and 5 (17.9%) patients in the robotic and control group, respectively. 8 (28.6%) wound infections in the control group and 0 in the robotic group.	100% at 6 months	100% at 6 months
Menon et al. (2013) [9]	25 RAKT	214 min	47 min	- Delayed graft function (16%); - Intraperitoneal hematoma (4%); - Infection (4%).	96% at 6 months	100% at 6 months
Tsai et al. (2014) [10]	10 RAKT	257.8 min	/	/	/	/
Doumerc et al. (2015) [11]	1 RAKT	200 min	/	No complication	/	/
Musquera et al. (2021) [12]	5 RAKT	220 min	53.2 min	1 case of ACR	/	/
Sood et al. (2015) [13]	54 RAKT	201.1 min	2.3 min	Facial edema (5.6%)	/	/
Breda et al. (2017) [14]	120 RAKT	250 min	2.0 min	1 case (0.8%) of wound infection, 3 cases (2.5%) of ileus, 4 cases (3.3%) of bleeding, 1 (0.8%) case of DVT, 1 case (0.8%) of lymphocele, 3 cases (2.5%) of transplantectomy due to massive arterial thrombosis, 5 cases (4.2%) of intraperitoneal hematoma.	/	/
Tzvetanov et al. (2020) [4]	239 RAKT	288 min	45 min	Wound complications (3.8%), 1 bleeding, 6 urinary leaks, 2 graft nephrectomy for hyperacute rejection and vascular thrombosis, 1 pancreatitis after SPK, 1 partial small bowel obstruction.	The patient survival at 1 and 3 years was 98% and 95%, respectively.	The graft survival at 1 and 3 years was 98% and 93%, respectively.
Spaggiari et al. (2020) [15]	9 (only KT) 11 (with SG)	269 min (only KT) 405 min (with SG)	/	1 surgical site infection (KT), 1 wound cellulitis (KT), 2 seromas or sterile hematoma (KT), 1 (KT + SG), 1 prolonged wound drainage (KT + SG)	/	/

3. Robotic-Assisted Pancreas Transplantation (RAPT)

The application of robotic technology to the pancreas transplant started simultaneously with RAKT. The expectations were high, especially regarding the potential facilitation of the surgical procedure compared to laparoscopy, the advantages in postoperative recovery, and the benefits for obese patients.

The very first RAPT was reported by Boggi and colleagues in 2012. They published a series of two solitary robotic pancreas transplants and one simultaneous pancreas–kidney (SPK) transplant. The mean cold ischemia time for the pancreas was of 7 h and 20 min. The operative time was 3 h for SPK and 5 h for the pancreas transplants alone and 8 h for the combined pancreas–kidney transplantation. The mean warm ischemia time was 35 min. No bleeding from the vascular anastomosis was recorded, and graft reperfusion was homogeneous. In one case, intraoperative bleeding from the mesenteric root was managed robotically, without requiring a conversion to open surgery. The mean blood loss was 170 mL, and none of the recipients required a blood transfusion. The postoperative course was uneventful for all patients. From a technical perspective, the pancreas was positioned above the right psoas muscle with vascular anastomosis to the distal inferior vena cava (IVC) and the right common iliac artery. A 7 cm midline incision was made to facilitate hand assistance in positioning the graft correctly, applying vascular clamps, and performing the duodeno-jejunal anastomosis, procedures traditionally conducted in an open approach. All patients became insulin-independent [23].

In 2018, Spaggiari et al. described their experience with five obese patients who underwent RAPT at the University of Illinois at Chicago between October 2015 and October 2016. Among them, four were men and one was a woman. Three cases were attributed to type 1 diabetes, while the remaining two were associated with type 2 diabetes. The distribution of obesity classes comprised two recipients with class I obesity, two with class II obesity, and one with class III obesity. Prior to surgery, the patients needed an average of 65 units of insulin per day. Among the recipients, three underwent SPK transplants, one received a pancreas after kidney transplantation, and one underwent pancreas transplantation alone. The authors chose to position the pancreas graft into the left iliac fossa with the head facing caudally. This positioning was chosen to achieve dorsal alignment of the portal vein with the left external iliac vein and ventral alignment of the arterial Y-graft with the external iliac artery. Both anastomoses were carried out in an end-to-side fashion. In the case of SPK, the robotic cart had to be redocked after completing the pancreas transplant, and symmetric contralateral ports for the robotic arms were placed on the opposite side. A 7 cm supraumbilical midline incision was performed for the insertion of organs and hand assistance, utilizing a GelPort [24]. Compared to Boggi's experience, the authors intentionally selected obese patients to emphasize the application of a minimally invasive technique for addressing surgical complications associated with obesity. While Boggi and colleagues manually applied vascular clamps through the GelPort, the authors opted for robotic application. Additionally, Boggi and colleagues manually conducted duodenal drainage through the GelPort, whereas the authors performed the anastomosis in a minimally invasive approach using the EEA circular stapler (Covidien, Mansfield, MA, USA) [23,24].

In 2018, Cantrell and Oberholzer published their technical experience. In their procedure, the pancreas remains cooled on ice until both the artery and vein are prepared. They utilize the external iliac vessels for vascular anastomosis, differing from the approach of Boggi et al. [23], who performed anastomosis on the distal inferior vena cava and the right common iliac artery. In robotic SPK transplants via a Pfannenstiel incision, they initially conducted the pancreas transplant on the right side, followed by the renal transplant on the left. Alternatively, when employing an epigastric incision, they positioned the pancreas on the left side and the kidney on the right [25].

In 2019, Spaggiari and colleagues reported their single-center retrospective study of pancreas transplant cases from January 2015 and December 2018, comparing robotic surgery to the open traditional approach. Forty-nine patients were enrolled (10 robotic, 39 open). The robotic technique was described previously by the same group. For the traditional approach, they used a midline incision. The Y-graft was anastomosed to the right common iliac artery, while the donor portal vein was anastomosed to the distal inferior vena cava (IVC), both performed in an end-to-side fashion. Pancreas drainage was accomplished through a two-layered end-to-side anastomosis connecting the duodenum to the distal jejunum. Patients undergoing robotic surgery exhibited a significantly higher BMI compared to those undergoing the open approach (33.7 ± 5.2 vs. 27.1 ± 6.6, $p = 0.005$). The robotic arm showed longer operative times (7.6 ± 1.6 vs. 5.3 ± 1.4, $p < 0.001$) and warm ischemia times [45.5 (IQR: 13.7) vs. 33 (7), $p < 0.001$], while the EBL was lower [150 (63) vs. 200 (350), $p = 0.042$]. The length of the hospitalization was shorter in the robotic arm, although this result did not reach statistical significance. Notably, there were no wound complications in the robotic approach patients. Two patients developed later an incisional hernia (one for the robotic approach on the epigastric incision, the other for the open arm on the midline scar), while two patients in the open approach group experienced duodenal stump leaks requiring re-operation (one resulted in graft loss, the other was managed with a Roux-en-Y duodeno-jejunostomy). One patient in the robotic arm exhibited an acute abdomen along with elevated pancreatic enzymes in the abdominal drain. Subsequently, she underwent exploratory laparoscopy which proved to be non-diagnostic. An abdominal lavage was performed, and the patient experienced an uneventful recovery from presumed pancreatitis. There were no statistically significant differences in the incidence of postoperative complications when comparing the two groups. Graft (100% vs. 88%, $p = 0.37$) and patient survival (100% vs. 100%, $p = 0.72$) after 1 year were similar [26].

These results confirm the feasibility and the safety of RAPT, compared to the open approach. Furthermore, as already stated for the RAKT, it is in the obese population that the robotic technology shows its benefits. More and more type 1 and type 2 diabetes mellitus patients are presenting with significant obesity, making them suboptimal transplant candidates at most centers. Obese patients face a higher risk of complications such as wound dehiscence, ventral hernias, intra-abdominal infections, gangrene, necrotizing infections, graft loss, and mortality [27,28]. This heightened risk may contribute to the hesitation observed in some centers to list these patients for pancreas transplantation. RAPT in obese candidates can represent the technical solution with the potential to mitigate the surgical complication risk and to grant access to pancreas transplantation in this underserved population. Further efforts must be made to facilitate the spread of robotic surgery in different centers, and, simultaneously, the complexity of robotic-assisted surgery requires high-volume centers and well-trained and long-experienced surgeons.

In 2021, the results of the First World Consensus Conference on Pancreas Transplantation were published. The primary message from this consensus conference is that both simultaneous pancreas–kidney transplantation (SPK) and pancreas transplantation alone have a positive impact on long-term patient survival, and all types of pancreas transplantation significantly enhance the quality of life of recipients. Pancreas transplantation may also positively influence the progression of chronic complications associated with diabetes, contingent on their severity. Consequently, the benefits of pancreas transplantation seem to clearly outweigh the potential disadvantages. In the case of pancreas after kidney transplantation, there is a higher risk of mortality only in the early post-transplantation period, but this is offset by improved life expectancy thereafter. Additionally, pre-emptive simultaneous pancreas–kidney transplantation (SPK), in contrast to SPK performed in patients undergoing dialysis, seems to be associated with better outcomes [29,30].

Table 2 presents the outcomes of these studies.

Table 2. Peri-operative outcomes in RAPT, RALiT, RALuT; SPK: simultaneous pancreas–kidney; RLDH: robotic liver donor hepatectomy.

Procedure	Authors	N° of Patients	Length of Procedure	Warm Ischemia Time	Complications	Patient Survival	Graft Survival
RAPT	Boggi et al. (2009) [23]	3	240 min (Pancreas only) 480 min (SPK)	35 min	No complication	/	/
RAPT	Spaggiari et al. (2019) [24]	5	456 min	45.5 min	1 patient exhibited an acute abdomen, 1 patient later developed an incisional hernia	/	/
RLDH	Giulianotti et al. (2011) [31]	1	480 min	35 min	No complication	/	/
Purely laparoscopic explant hepatectomy and laparoscopic graft implantation	Suh et al. (2021) [32]	1	369 min (hepatectomy) 960 min (total procedure)	84 min	No complication	/	/

Table 2. *Cont.*

Procedure	Authors	N° of Patients	Length of Procedure	Warm Ischemia Time	Complications	Patient Survival	Graft Survival
Purely laparoscopic explant hepatectomy and hybrid laparoscopic/robotic graft implantation	Suh et al. (2022) [33]	1	1065 min	/	No major complication	/	/
RALuT	Jiao et al. (2023) [34]	1	/	/	/	/	/
RALuT	Emerson et al. (2023) [35]	1	/	88 min	No major complication	/	/

4. Robotic-Assisted Liver Transplantation (RALiT)

While early experiences of RAKT and RAPT have been documented in the literature, to the best of our knowledge, there is no published report of a fully robotic liver transplant. The liver transplant procedure is more complex due to the necessity of explanting the native organ for subsequent graft implantation (orthotopic transplant), whereas kidney and pancreas transplants are typically placed in the iliac fossa (heterotopic transplant). Therefore, the application of minimally invasive surgery (MIS) in liver transplantation must address both the explantation phase and the subsequent placement of the new organ.

The first application of robotic technology to liver transplants dates back to 2011. Giulianotti and colleagues published the first case report of robot-assisted right lobe donor hepatectomy (RLDH). The procedure was conducted using the DaVinci Surgical System, with a fully minimally invasive approach. The liver graft was safely retrieved using a lower abdominal incision. The operative time was 8 h, and the blood loss was 350 mL. The liver graft was successfully implanted, with cold and warm ischemia time of 25 and 35 min, respectively. Both the donor and the recipient experienced smooth recoveries without acute complications. The donor was discharged home on postoperative day 5, the recipient on postoperative day 8 [31]. Since then, the use of MIS has been spreading, but it remained confined to graft procurement in living donors.

We had to wait until 2021 when Suh and colleagues published the first case of pure laparoscopic hepatectomy and pure laparoscopic implantation of the graft. The procedure consisted of a fully laparoscopic hepatectomy without liver fragmentation in a 60-year-old man with alcoholic liver cirrhosis and hepatocellular carcinoma, where the explanted liver was extracted through a suprapubic incision. A modified right liver graft, procured from his 24-year-old son with a pure laparoscopic fashion, was delivered through the suprapubic incision, and implantation was performed intracorporeally. The hepatectomy time was 369 min, with a total operative time of 960 min. The times required for the anastomosis of the hepatic vein, portal vein, hepatic artery, and bile duct were 42, 34, 49, and 45 min, respectively. The warm ischemia time was 84 min, and the portal vein was clamped for 212 min. The EBL was 3300 mL, and five units of red blood cells were transfused during the procedure. A protocol CT scan performed on postoperative day 7 revealed patent vascular structures without any abnormal findings. The postoperative course was uneventful, and the patient was discharged on postoperative day 11 [33].

The following year, in 2022, the same group of Suh et al. published the first report of pure laparoscopic hepatectomy and hybrid laparoscopic/robotic graft implantation in living donor liver transplantation. A suprapubic incision was performed to retrieve the native organ and to deliver the graft. The EBL was 11,500 mL, and 20 packs of red blood cells, 16 packs of fresh frozen plasma, and one pack of plateletpheresis were transfused during the procedure. A protocol CT scan on postoperative day 7 confirmed a regular postoperative course. The patient was discharged on postoperative day 13, and no major complications were recorded. The reconstruction of the hepatic and portal veins was performed with a purely laparoscopic technique, while the robot was used for the arterial and bile anastomoses. Hence, the robot was docked immediately after the porta reperfusion. There was significant bleeding at the suprapubic incision site. This was not identified properly during the robotic phase, but only at the end of it. Multiple factors made the source of bleeding difficult to recognize. Firstly, the patient was positioned in reverse Trendelenburg. Secondly, the robotic arms were primarily focused on the hepatic hilar area during reconstruction, limiting the range of motion, including the camera view [32].

After this hybrid laparoscopic/robotic experience, in 2023, the first fully robotic liver transplantation was performed by the Organ Transplant Center of Excellence (OTCoE) at the King Faisal Specialist Hospital & Research Centre (KFSH&RC) in Riyadh, Saudi Arabia. The recipient of the liver was a 66-year-old Saudi male battling non-alcoholic liver cirrhosis (NASH) and hepatocellular carcinoma (HCC). In the same period, the surgical team from Washington University School of Medicine in St. Louis, United States, performed the first robotic liver transplant in the U.S. The patient was a 60-year-old male who needed a transplant because of liver cancer and cirrhosis caused by hepatitis C virus. Despite the absence of official reports on these early accomplishments, the successful completion of the first fully robotic liver transplants has been achieved. Further studies, including a prospective cohort study to monitor immediate outcomes and a comparative study comparing traditional methods, are needed to thoroughly evaluate the procedure's feasibility and safety.

In summarizing the reported experiences, key considerations for the robotic approach and MIS emerge. Firstly, patient and graft selection play crucial roles: patients with ascites and a large abdomen provide a larger and more ergonomic working space for a robotic approach; moreover, ensuring the size of the graft is appropriate relative to the recipient's body habitus is essential for a comfortable surgical field. Secondly, the presence of varices or shunts may prevent bowel congestion during hilum dissection and portal vein clamping. However, significant collateral venous drainage may also increase the risk of major bleeding during the dissection phase. Thirdly, during hilum dissection, dividing the right vessels while preserving the left side may help prevent visceral congestion. Lastly, the fragmentation of the native liver, particularly parenchymal transection as in a left lateral sectionectomy, can aid in exposing the IVC. However, the fragmentation of the liver parenchyma may increase the risk of cancer exposure and dissemination (in case of primitive liver cancer, metastasis, or unknown cancer on cirrhotic liver). The utilization of intraoperative ultrasound is valuable for ensuring secure and safe margins. A significant drawback associated with the robotic approach lies in the prolonged operation time, coupled with extended warm ischemia. Nonetheless, it is crucial to recognize that ongoing training and accumulated experience have the potential to mitigate these challenges, possibly leading to reduced total operation and ischemic times in the future. As mentioned before for RAKTs and RAPTs, the greatest benefits gained from the MIS/robotic application include enhanced postoperative recovery, decreased risk of wound complications such as hematoma, infection, and incisional hernia, lowered likelihood of lung infections, accelerated muscle rehabilitation, and reduced total length of hospital stay. However, there are currently no published cases of obese patients undergoing RALiT, despite the potential for the robotic approach to offer significant advantages in this patient population.

Robotic versus Laparoscopic Donor Hepatectomy

Few studies in the literature highlight the differences in terms of perioperative outcomes between laparoscopic and robotic living donor hepatectomy. A study by Kim et al. [36] provides valuable insights into this comparison. In their cohort analysis, they discovered that operative time and graft-out time were notably longer for RLDRH. However, it is noteworthy that this technique was associated with a significant reduction in EBL. Contrastingly, in their experience, warm ischemia time and the occurrence of severe postoperative complications, categorized as Clavien–Dindo Grade III or above, were found to be similar with both laparoscopic and robotic techniques.

5. Robotic-Assisted Lung Transplantation (RALuT)

In February 2023, the Chinese group of Jiao and colleagues published the first case of robot-assisted single lung transplantation (RALuT) for a patient with end-stage chronic obstructive pulmonary disease (COPD). The recipient had undergone bilateral pulmonary bullae resection via thoracotomy 10 years earlier. A DaVinci Si Surgical System was used for the transplantation. After the division of extensive pleural adhesions and of lung hilum (pulmonary vessels and main bronchus), the right lung was removed through an 8 cm-wide assistant incision. The donor's lung was prepared with a cold ischemic time of 300 min and placed into the chest cavity via the same 8 cm assistant incision. The reconstruction phase was fully robotic, starting with the bronchial anastomosis followed by the anastomosis of the pulmonary artery and atrial cuff. No intraoperative or postoperative complications were reported. On postoperative day 9, chest CT showed compatible post-transplantation lung expansion. The patient was discharged on postoperative day 19 [34].

A few months later, in September 2023, a new case of a full RALuT was reported by Emerson and colleagues. The patient was a 69-year-old man, with a diagnosis of end-stage chronic obstructive pulmonary disease refractory to medical management and oxygen-dependent at baseline. Due to the patient's favorable anatomy and need for a right single lung transplant, he was approached as a possible candidate for an RALuT. The bronchial anastomosis was performed first. After that, the left atrial anastomosis was completed using the DaVinci system. After completing this anastomosis, it was determined that the pulmonary artery anastomosis should be completed under direct vision due to the relatively longer ischemic time at that point (nearly 70 min), and some challenges placing the pulmonary artery clamp. The DaVinci system was then undocked, and the pulmonary artery anastomosis was completed in the standard open fashion, using the same 6 cm incision used to remove the primitive organ and to insert the graft, without the need of enlarging it. The hospital course was uneventful other than an episode of atrial fibrillation, which was treated with amiodarone. The patient was discharged to home on postoperative day 11 [35]. Attached to the description of this first experience, the group of Emerson also mentioned their initial series of eight RALuTs, including five single lung transplants and three bilateral. Among them, two additional cases were performed with traditional open pulmonary artery anastomoses (case 3, and the left lung in case 7), due to high pulmonary artery pressures. Additionally, given the high pulmonary pressure and the need to initiate ECMO support, the left lung in case 5 (bilateral RALuT) was implanted in a traditional manner. Warm ischemic times have generally trended down, from a high of 111 minutes to around 1 h in recent cases [35].

These initial results show promise for the application of robotics in lung transplantation. While the necessity to perform artery anastomoses in a traditional open fashion is deemed acceptable in these early experiences, the fact that it was accomplished using the same small thoracic incision underscores the benefits of the robotic approach and supports the efforts towards achieving a full RALuT. Certainly, further experience, including cases performed at other transplant centers is required, but this early success at least indicates feasibility and gives hope for potential wider use in the future.

6. Conclusions

Robotic-assisted transplantation has consistently showcased its feasibility, although this achievement comes with the caveat of enduring lengthy and potentially risky operations. The integration of robotics in kidney transplantation is becoming increasingly prevalent, especially in specialized centers, particularly for the procurement of grafts from living donors. However, when it comes to liver, pancreas, and lung transplants, these procedures demand a higher level of expertise, coming with specialized training and the background of experienced centers. Nonetheless, the adoption of robotic techniques is steadily gaining momentum even in these more intricate fields, with successful outcomes supported by recent reports in the medical literature. The wider adoption of robotic platforms and enhanced training protocols are likely to mitigate the disparities in terms of both operative time and warm ischemia time, which tend to be longer in robotic-assisted procedures. Further pioneering applications and comprehensive studies will be essential to confirm the advantages of robotic-assisted transplantation. Throughout this process, maintaining informed patient consent remains paramount to ensure proper transparency and foster patient understanding.

Author Contributions: Conceptualization, M.D.P., F.P. and F.G.; methodology, M.D.P., A.M., F.T. and G.P.; validation, F.G.; writing—original draft preparation, M.D.P., F.P., A.M., F.T., G.P. and F.G.; writing—review and editing, F.P., F.T. and G.P.; supervision, F.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

End-stage renal disease (ESRD); minimally invasive surgery (MIS); pancreas after kidney (PAK); pancreas transplant alone (PTA); right lobe donor hepatectomy (RLDH); robot-assisted surgery (RAS); robotic-assisted kidney transplant (RAKT); robotic-assisted liver transplantation (RALiT); robotic-assisted pancreas transplant (RAPT); robotic-assisted lung transplant (RALuT); surgical site infections (SSI); simultaneous pancreas–kidney (SPK).

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