Robot-Assisted Transplant Surgery – Vision or Reality? A Comprehensive Review

Philipp Stiegler^{a, b} Peter Schemmer^{a, b}

^aDivision of Transplant Surgery, Department of Surgery, Medical University of Graz, Graz, Austria;

^bTransplant Center Graz, Medical University of Graz, Graz, Austria

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Summary

Minimally invasive surgery is standard procedure for many operations. Further refinements include the introduction of robotic surgery which is still an emerging field especially in laparoscopic surgery. Since the successful introduction of the da Vinci Robotic Surgical System, the robotic approach in organ transplantation has become of great interest in both the live donor organ retrieval and the recipient operation. Robotic surgery for kidney, liver, and pancreas transplantation is feasible. Over 700 donor nephrectomies and 100 kidney transplantations have been performed already, and robotic surgery is standard in a small number of pioneer centers; however, larger series and most importantly randomized controlled trials for the highest evidence are needed. Longer warm ischemia time and higher costs limit these procedures at the moment.

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Introduction

During the last decades, minimally invasive surgery has become standard procedure in many operations. Further developments include robotic surgery which is an emerging field especially in laparoscopic surgery. Meanwhile a few robotic systems with various abilities and price tags have been developed by different companies.

The rapid development of both equipment including camera systems, insufflators for pneumoperitoneum, and instruments, as well as surgical techniques for minimally invasive approaches have changed surgery over the past few years. In addition to the benefits provided by conventional laparoscopic surgery, the robotic systems for robotic-assisted surgery (RAS) are supposed to help to overcome reduced visualization, restricted range of motion, and even physiological tremor of the surgeon [1]. Feasibility and safety in performing a challenging and complex procedure with RAS is given [2]; however, RAS if compared with conventional open surgery as well as conventional laparoscopic surgery is associated with much higher costs that come along with the inevitable use of specially designed high-end equipment and length of procedure including the time needed to set up the system in the operating room for every case.

With conventional laparoscopic surgical techniques, some very complex procedures such as organ transplantation have not been considered as suitable for minimally invasive surgery [3]; however, after the introduction of modern precise surgical robotic systems like the da Vinci Surgical System (daVSS) (Intuitive Surgical, Sunnyvale, CA, USA), the surgeons' ability has expanded and even organ transplantation is considered to be performed in a minimally invasive fashion with RAS [4].

The main advantages of the daVSS compared with conventional laparoscopic surgery are i) the 3-dimensional (3D) view which completely restores hand-eye coordination and even includes a possible 10× and 15× magnification of the operative field if needed, while the operative field remains steady with the camera driven by the surgeon who is doing the procedure; ii) the instruments provide a distal articulation similar to the human wrist (EndoWrist®, Intuitive Surgical) with 7 degrees of freedom, thus EndoWrist totally avoids the fulcrum effect of conventional laparoscopic surgery; and iii) the physiological human tremor is eliminated by motion scaling which is achieved with the device tracking the surgeon's movements 1,300 times per second.

Based on the features of RAS stated above, the minimally invasive approach in organ transplantation has become of great interest in both the live donor organ retrieval and the recipient operation, but suitability and cost effectiveness have to be carefully investigated.

In 1995, Ratner et al. [5] introduced the concept of minimally invasive live donor kidney graft retrieval. This totally laparoscopic approach was used in 2001 by Gruessner et al. [6] who then reported the first laparoscopic pancreatic graft retrieval in a live donor, followed by Soubrane et al. [7] who performed the first laparoscopic left lateral liver resection in a live donor for pediatric transplantation in 2006. Since 2002, the use of RAS has been steadily increasing in transplant surgery.

Kidney Transplantation

Kidney transplantation (KTx) is the treatment of choice in end-stage renal disease. Kidney is the most frequently transplanted solid organ, and the most experience with RAS has been gained in both donors and recipients in the setting of living related KTx [8].

Live Kidney Donation

Previous research has clearly shown both superior survival of kidney grafts from live donors after transplantation and fewer postoperative complications [9, 10].

While the conventional surgical approach with a mini-incision for open live donor nephrectomy has been shown to significantly reduce morbidity compared to historic open approaches [11–14], laparoscopic transperitoneal donor nephrectomy has become standard procedure for the procurement of live donor kidneys due to better visibility of the operative field in many centers [9] being associated with a short hospital stay, less pain, and fast recovery after surgery in some studies [15, 16].

In the past decade, new developments and improvements in operating techniques and imaging, such as RAS, have been implemented. This has led to the implementation of robotic-assisted donor nephrectomy (RADN) in some centers [17]. The first series of 12 successful RADN were performed with daVSS [17]. Since then, over 700 RADNs have been reported (table 1).

Surgical Procedure

Briefly, for a left live donor nephrectomy, the patient is in a right lateral decubitus position supported with a cushioned beanbag and axillary roll. Adequate fixation of the patient on the operating table is mandatory, because any instability after docking the robotic system could jeopardize the safety of the procedure [4]. Transabdominal RADN is usually performed with 4 laparoscopic ports (3 8-mm and 1 12-mm camera port, and if needed an additional 12-mm assistant port) and 1 7-cm infraumbilical incision [4].

Once the trocars are in place and the instruments inserted together with the optical system, the procedure is started with the mobilization of the left colon including the transection of the sple-

nocolic ligament. A space is created between the left mesocolon and Gerota's fascia. This preparation allows bloodless exposure of the left kidney's anterior surface. Subsequently, the kidney is freed from its fatty capsule; the ureter is dissected free and cut distally where it crosses the iliac vessels. Before cutting the ureter, a Hem-o-lok clip can be put distally on both the ureter and the gonadal vein. Now the renal vessels are exposed to its junction with the inferior vena cava and aorta. The renal vessels then are stapled or clipped close to the large vessels by the assistant surgeon. After rapid removal from the abdominal cavity, the kidney is rinsed with cold preservation solution.

Left kidneys are preferred live grafts because of the anatomical features of the right kidney which has a shorter length and greater fragility of its vein; however, the RADN procedure is the same with the live donor placed in the left decubitus position.

Usually, the patient is encouraged to ambulate the same day, and if no complications occur, the donor is discharged home on the second or third postoperative day [4].

Results

Tzvetanov et al. [4] analyzed a series of about 700 RADNs and reported only a limited number of complications. The most important complications, requiring conversion to open procedure, occurred at the beginning of the learning curve and included 3 cases of intraoperative renal artery stump bleeding and a single case of intraoperative renal vein laceration.

The initial graft survival and function rates and donor morbidity appeared to be very similar to the data from open living donor nephrectomy [18].

Recently, Janki et al. [9] compared RADN to hand-assisted retroperitoneoscopic donor nephrectomy (HARP) and standard laparoscopic kidney (LDN) procurement. There was a significantly longer median total operative time with RADN compared to both LDN and HARP. Further, warm ischemia time (WIT) in RADN was significantly longer as compared to all the other live organ donor procedures. Complication rate as well as graft and patient survival after 3 months were independent of the procedure. The results of this study are also comparable with other current studies describing RADN procedures for operative time [19], warm ischemia [19, 20], and length of hospital stay [19], which do not show clear superiority of RADN over the other modalities described.

The largest study published by Horgan et al. [17] including 250 living kidney donors shows that the mean operative time was strongly reduced with an increasing number of RADNs performed. Janki et al. [9] showed a significant improvement in total operative time after 60 RADNs performed, indicating the importance of the learning curve in RADN.

Up to now, approximately 700 cases of robotic living donor nephrectomy have been described in literature as compiled in table 1 [8].

Limitations that relate to the robotic system include prolonged set-up time and difficult instrument exchange which occur more frequently at the beginning of the learning curve [21].

The series presented by Janki et al. [9] showed that left-sided RADN is safe and feasible with good outcomes for donor, recipient, and graft survival after 3 months of follow-up. The RADN procedure might take longer; however, 3D imaging, better instrument movement, and comfort are gained. Although there is no scientific study evaluating the clinical pathway of robotic surgery training, a minimal caseload is necessary to maintain surgical robotic skills and technicity. For experienced endoscopically trained surgeons, the operative time will improve significantly and approximate the operative time of other surgical techniques [9].

Bhattu et al. [22] performed a randomized controlled trial with 54 kidney donors and compared RADN to LDN. They concluded that RADN is safe and associated with a better morbidity profile than LDN. The robotic approach provides technical ease and facilitates preservation of a longer length of the renal artery on the right side. The authors stated that left-sided RADN is associated with longer WIT but did not find any negative influence on graft outcome.

Taking into consideration all the data presented above, RADN appears to be feasible; however, with regard to WIT and higher costs, the procedure seems to be limited to certain case series, especially within high-volume centers.

Kidney Transplantation Techniques

Today's techniques in KT_x include conventional laparoscopic (transperitoneal or retroperitoneal), robotic-assisted, as well as open minimal-access KT_x [11].

Despite the advantages mentioned above, possible adverse effects such as prolonged WIT and operative time have to be considered. WIT is known to be a negative cofounder for graft injury [11, 23]. Recently, Marzouk et al. [11, 23] reported that anastomosis time >29 min significantly increases postoperative delayed graft function. Weissenbacher et al. [24] showed significant negative effects of prolonged anastomosis time >30 min for patients and graft survival, and therefore robotic-assisted kidney transplantation (RAKT) should only be performed in high-volume centers with large expertise in RAS in order to avoid negative effects on the kidney graft due to long WIT and anastomosis time. Thus, strategies to minimize WIT in RAKT have to be developed. Menon et al. [25] reported a new technique for intraperitoneal cooling of the allograft with ice slush in order to reduce WIT.

Hoznek et al. [26] published a first and single case of robotic assistance during KT_x in which an open access to the iliac fossa was established and dissection of the vessels with subsequent anastomosis was performed using the robot [8]. Later, the first complete RAKT was published in the US by Giulianotti et al. [27]. This operation took 230 min with a WIT of 50 min. Boggi et al. [28] reported the first RAKT in Europe 2 years later [8]. During the last decades, laparoscopic KT_x has been replaced by RAKT in some high-volume centers. Menon et al. [25] standardized RAKT and performed 50 cases purely robotically. While Menon et al. [25] used RAKT in normal-weight recipients, Tzventanov et al. [4] used RAS especially in obese patients.

Table 1. Robotic-assisted surgery in kidney transplantation (KT_x)

Author	Reference	Live left kidney retrieval	Live right kidney retrieval	KT _x
Abaza	[59]	0	0	39
Bhattu	[22]	9	6	0
Boggi	[28, 51]	0	0	2
Breda	[60]	0	0	17
Cohen	[61]	79	21	0
Galvani	[21]	1	0	0
Giacomoni	[20]	16	0	0
Giulianotti	[27]	0	0	1
Gordon	[62]	1	0	1
Gorodner	[63]	209	4	0
Horgan	[17]	254	19	0
Hoznek	[26]	0	0	1
Hubert	[64]	12	8	0
Janki	[65]	59	0	0
Kaouk	[36]	1	0	0
Laplace	[31]	85	0	0
Liu	[19]	0	5	0
Louis	[66]	34	1	0
Meier	[67]	0	0	17
Menon	[25]	0	0	50
Oberholzer	[34]	0	0	75
Renoult	[18]	12	4	0
Sood	[68–70]	0	0	160
Tsai	[29]	0	0	10
Tzventanov	[4]	0	0	70

Surgical Procedure

Back table preparation for robotic implantation includes specific steps in order to facilitate orientation of the organ and minimize bleeding after reperfusion.

Transperitoneal KT_x is carried out via 4 laparoscopic ports (2 12-mm and 2 7-mm ports) and a 7-cm midline incision for the hand port. The patient is placed in a 30° Trendelenburg position with the right side elevated for transplantation in the right iliac fossa. The robotic system is docked into position at the patient's right leg [4].

After mobilization of the right colon, the right iliac vessels are exposed. Once the external iliac vein is completely dissected and clamped with bulldogs, a venotomy for end-to-side anastomosis with running suture is performed. Subsequently, a side-to-end arterial anastomosis is performed likewise. Clamps are removed for reperfusion of the graft. At this point, the pressure of the pneumoperitoneum is decreased to minimize a possible negative effect of high intra-abdominal pressure on graft perfusion. Finally, the ureter is anastomosed to the bladder.

Most of the studies reported in the literature have been performed transabdominally. Tsai et al. [29] recently reported initial experiences in robot-assisted retroperitoneal KT_x with promising results.

Results

Menon et al. [25] have shown results with a mean creatinine at discharge of 1.3 mg/dl which is comparable with conventional

techniques. There were no intraoperative and postoperative complications at 6-month follow-up. Breda et al. [30] applied regional hypothermia in 17 RAKTs with no major surgical intraoperative complication; however, delayed graft function, graft arterial thrombosis, and intraperitoneal hematoma appeared in single patients. A series of 100 RAKTs with 99% of immediate renal graft function recovery was published by Laplace et al. [31].

In obese patients, surgical site infections (SSI) were absent and results were similar to non-obese recipients [32]. These results show the importance of implementing new surgical techniques in obese KTx recipients that can prevent complications such as SSI. The authors describe their results in more than 70 RAKTs in obese patients and did not observe any SSI within the first 30 days after transplantation [4]. The hypothesis that RAS is a safe procedure in such patients is supported by data by Garcia-Roca et al. [33] showing excellent patient and graft survival with a renal function comparable to open techniques. This was also confirmed by Oberholzer et al. [34].

As WIT is crucial in KTx, the use of a robotic system for kidney implantation does not seem to be justified as the results do not show superiority to conventional KTx. Therefore, RAKT at the moment should be limited to obese patients who seem to clearly benefit from this method. Furthermore, besides transplantation, robot-assisted procedures have been described in KTx recipients for the management of surgical complications, such as cases of pyeloureterostomy for ureteral stricture [35], partial nephrectomy for the treatment of a renal mass in a transplanted kidney [36], transabdominal graft nephrectomy [37], and radical prostatectomy for prostate cancer treatment in kidney transplant recipients [38] with good results.

Liver Transplantation

Living donation is one of the tools to increase the donor pool thus reducing the lack of livers suitable for transplantation from deceased donors. Live donor right hepatectomy has become the most common procedure in living related adult-to-adult liver transplantation (LTx) and is a widely accepted alternative to deceased donor LTx [11, 39]; however, there are concerns regarding the safety of healthy volunteer live organ donors [2]. Complication rates of living liver donors range between 16 and 34% [40].

The laparoscopic approach for right lobe live liver donation seems to be advantageous since 30–50% of the complications in open cases are associated with trauma to the abdominal wall, i.e. hernia, bowel obstruction, and chronic abdominal discomfort [41]. Studies on robotic-assisted live liver donation are compiled in table 2.

Living-Donor Hepatectomy

RAS techniques have shown advantages in patients undergoing major hepatectomy [42]. The first report of a robotic live donor right hepatectomy was by Giulianotti et al. [43] in 2012. A recent

Table 2. Robotic-assisted surgery in liver transplantation

Author	Reference	Live liver retrieval
Chen	[2]	13 (right lobe)
Giulianotti	[43]	1 (right lobe)
Wu	[71]	1 (left lobe)

Table 3. Robotic-assisted surgery in pancreas transplantation (PTx)

Author	Reference	Live pancreas retrieval	PTx
Boggi	[52]		3
Horgan	[49]	1	
Yeh	[53]		1

review suggested that robotic liver resection is at least comparable to both open and laparoscopic procedures based on outcome [44]. No differences between robotic and open donor right hepatectomy but less postoperative pain control associated with pneumonia in favor of the robotic procedure were described [2, 4].

Surgical Procedure

In supine 20° reverse Trendelenburg position with parted legs, the procedure is performed using 3 trocars (12 mm) for the robotic arms, 2 assistant ports (12 and 5 mm), and a camera port [44]. Usually, the liver is freed from the hepatic ligaments and the hilum dissected free together with both the right hepatic artery and portal vein for liver right donor hepatectomy. This and the other steps including parenchymal dissection, division of vessels, cholangiography, and sonography are very much standard irrespective of the approach. The donor graft is retrieved through a 8- to 10-cm Pfannenstiel incision and subsequently rinsed with cold perfusion solution [4].

Results

While the operative time in live donor right hepatectomy is significantly longer compared with open procedures, there is no difference in complication rates, blood loss, and postoperative function of the liver remnant [2, 45]. Decreased overall morbidity and intensive care unit and hospital stay are in favor of laparoscopic procedures while the operation per se adds tremendously to treatment cost, especially in the case of robotic systems being used. Taking into consideration the higher costs as well as the longer operating time, robotic-assisted donor right hepatectomy is not advantageous over conventional laparoscopic approaches [45].

Although the procedure should only be performed by experienced surgeons, robotic surgery might play an important role in establishing a standard procedure for minimally invasive liver donor surgery and especially in living liver donation.

Pancreas Transplantation

Pancreatic transplantation (PTx) is the only method to restore physiological glycemic control and prevent progression of com-

plications in diabetic patients [46]. Refinements in surgical technique and immunosuppressive therapy have considerably improved outcome; however, the complication rate remains still at about 25% [47].

Pancreas Donation

Live pancreatic donation for transplantation is very rare [48] (table 3). Distal live donor pancreatectomy with spleen preservation [8] is meant to decrease the morbidity and mortality of diabetic patients who have potential donors [34]. Since PTx is simultaneously performed with KTx, a possible advantage of minimally invasive surgery for live donation is that once the left kidney is removed, the inferior border of the pancreatic tail is already partially dissected [8]. The first robotic hand-assisted simultaneous nephrectomy and distal pancreatectomy was described in 2007 by Horgan et al. [49].

Surgical Procedure

Horgan et al. [49] reported a single case of RADN with daVSS for live donor pancreatic tail retrieval for transplantation. Briefly, the splenic artery and vein were isolated and divided distally close to the hilum of the spleen and were isolated to the celiac trunk and portal vein, respectively. The parenchymal transection was performed at the junction between the body and the head of the pancreas. The organ was removed and underwent back table preparation subsequent to cold preservation [4].

Pancreatic Transplantation

PTx still remains the treatment of choice for patients suffering from insulin-dependent type I diabetes. While there is a great number of potential recipients [50], PTx continues to be offered only to highly affected individuals who have poor quality of life under conventional insulin therapy [51]. The laparoscopic approach to PTx has improved outcome [52]; well-known limitations in conventional laparoscopic surgery restrict the use in PTx to experts in this field [3]. Boggi et al. [51] have shown how to overcome these limitations with RAS for PTx.

Yeh et al. [53] performed the first RAS for pancreas after KTx in 1 severely obese patient. Excellent metabolic control was achieved, and the patient remained in a nondiabetic status during the follow-up period.

However, taking into consideration the longer WIT as well as higher costs and operating time, robotic-assisted pancreatic donation and transplantation are not superior to conventional open approaches.

Surgical Procedure

Careful in situ preparation during the cadaveric donor organ retrieval is required to avoid bleeding at transplantation [52]. During the back table operation, the pancreatic graft's vasculature must be

reconstructed with a donor-Y-iliac graft as used in standard conventional PTx. A small midline incision is needed to insert the graft into the abdomen. Subsequently, the pancreas is placed behind the right colon. The proximal vena cava is anastomosed to the superior mesenteric vein due to larger caliber and easier handling. Donor-Y-graft is anastomosed to the recipient's common iliac artery. The duodeno-jejunal anastomosis is performed open with a Roux-en-Y loop reconstruction.

In contrast to standard open simultaneous P/KTx, Fridell et al. [54] placed both grafts on the right side of the recipient without modifying the patient's position; however, for the uretero-vesical anastomosis, repositioning of the patient and the robotic system would have been needed. Due to time limitations, an open approach for this step is recommended.

Results

PTx with daVSS is feasible [51, 55]; however, the benefits of RAS in this procedure are limited [51] and today's standard must be changed towards the use of a robotic system with major steps still performed in an open fashion [56]. For cooling the graft during PTx, a pancreas jacket has been developed [57].

Conclusion

Robotic-assisted transplantation is feasible and has already been performed for KTx, PTx, and uterus transplantation by a few pioneers in the field of RAS. While there are major obstacles in the recipient operation, robotic-assisted live kidney retrieval has become standard procedure in some centers. Despite the enthusiasm for the emerging RAS in transplantation, widespread use is limited due to current costs, longer operating times, and, in what is most crucial in transplantation, longer WIT [34, 58].

In the future, the issues of WIT and cold storage must be carefully addressed in the setting of RAS for transplantation. The gold standards and requirements for the highly standardized conventional technique must also remain valid for RAS.

The use of RAS in transplantation has to be carefully considered in high-performing centers but does not show clear superiority to conventional transplantation techniques according to the current literature.

Since, to date, cases in which the entire operation has been performed using RAS are rare in transplantation surgery, a comparison in between conventional laparoscopic and RAS cases with a focus on transplantation is not conducive; however, successful transplantation seems to be feasible using the synergies between RAS and conventional laparoscopic surgery.

Disclosure Statement

The authors have no conflict of interest to declare.

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