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REVIEW

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Clinical advances in kidney autotransplantation: a review

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Abstract

Kidney autotransplantation is a surgical procedure with multiple indications and advancing technological approaches. Kidney autotransplantation is used to address complex kidney-related diseases including renal vascular lesions, ureteral diseases, tumors, loin pain-hematuria syndrome, and conditions affecting a solitary kidney or both kidneys. Renal artery lesions, including aneurysms and stenoses, often necessitate kidney autotransplantation in cases involving renal artery bifurcation or distant failure of endovascular repair. Complex ureteral lesions such as ureteral avulsions are commonly treated with kidney autotransplantation. Renal tumors, especially centrally located tumors or those involving the renal hilum, are treated using this technique while preserving renal function. It is worth emphasizing that this would be a rarely used last-resort technique in the modern era of minimally invasive nephron-sparing surgery. Kidney autotransplantation may be indicated for the rare condition of loin pain-hematuria syndrome when conservative measures fail. Additionally, individuals with solitary or bilateral kidney disease benefit from kidney autotransplantation to preserve their renal function. Traditional open-kidney autotransplantation involves renal extraction, workbench repair, and renal reimplantation. Technological advancements have introduced minimally invasive techniques including laparoscopic- and robot-assisted kidney autotransplantation, which reduce surgical trauma and recovery times. These techniques have shown promising outcomes, and robotic platforms have the potential to further reduce complications. In this study, we reviewed diverse indications and recent technological innovations in the field of kidney autotransplantation.

Keywords Kidney autotransplantation, Kidney transplantation, Autotransplantation, Kidney-related diseases, Minimally invasive surgery

Background

Kidney transplantation can be categorized as allogeneic, autologous, and xenogeneic, depending on the source of the donor kidney. Kidney autotransplantation (KAT) was pioneered by Hardy in humans and has been successful in the treatment of upper ureteral stenosis [1]. Subsequently, the application of KAT was expanded to encompass renal vascular lesions, tumors, and loin pain-hematuria syndrome. In a retrospective analysis of the US Nationwide Inpatient Sample database, Moghadamyeghaneh et al. [2] identified renal artery lesions (22.7%), ureteral diseases (17%), and malignancies (14.9%) as the

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most prevalent surgical indications for KAT. Renal failure occurred in 10.7% of the cases, with overall mortality and complication rates of 1.3% and 46.2%, respectively. Recent advancements in the clinical use of KAT have emerged, largely owing to the widespread adoption of minimally invasive surgical techniques. This study aimed to provide an overview of the clinical developments in both the indications for and technological advancements in the field of KAT(Fig. 1).

Indications

Renal vascular lesions

Renal artery lesions

Renal artery aneurysms are uncommon, with 0.1% of the population experiencing renal artery aneurysms [3]. Typically, renal artery aneurysms are asymptomatic [4]. The currently recognized criteria for intervention in renal artery aneurysms include aneurysm size > 2 cm, presence in women of reproductive age, associated pain, hematuria, and drug-refractory hypertension [3]. Notably, approximately 70% of individuals with renal artery aneurysms also have hypertension, with some studies reporting this figure as high as 100% [3]. The primary treatment for renal artery aneurysms requiring intervention is surgical repair, including KAT. Earlier data indicated a preference for surgical repair over endovascular repair [5]. However, as endovascular technology advances, it is increasingly preferred owing to its lower complication rates and shorter hospital stays [5–7]. A meta-analysis conducted by Choksi et al. found no significant differences in mean aneurysm diameter, overall complications, and mortality between endovascular repair, surgical

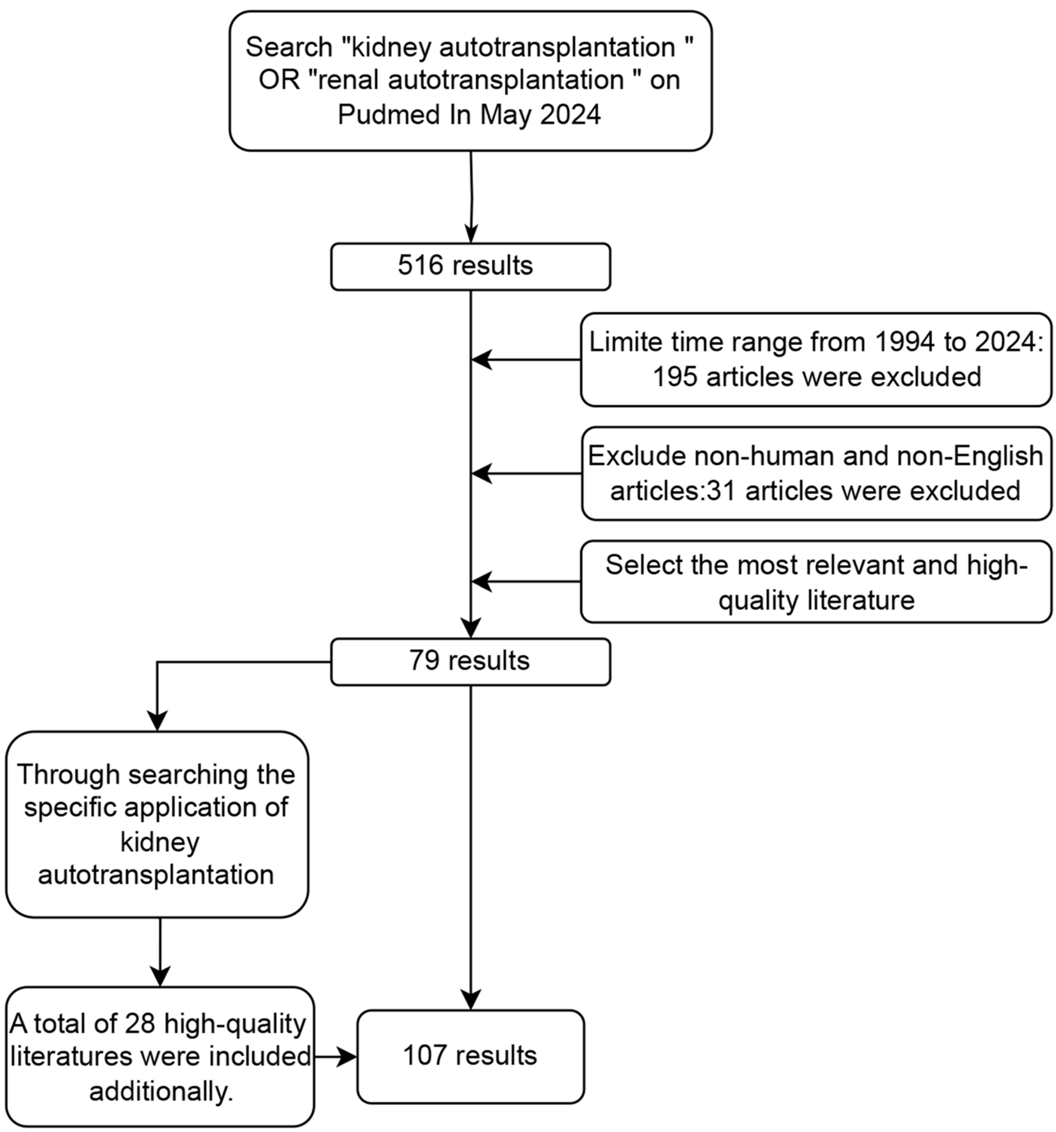


Fig. 1 Flowchart of the study

repair, and KAT [8]. Renal artery aneurysms located on the main trunk of the renal artery are suitable for endovascular repair [9, 10]. Conversely, complex renal artery aneurysms (such as those involving renal artery bifurcations or those with distant lesions [3, 8, 10, 11], failure of endovascular repair [12], and anatomical structures that are not suitable for endovascular treatment [10]) may require surgical repair, including KAT. Notably, the first bifurcation of the renal artery is the most common site for renal artery aneurysms [4, 7, 13]. KAT effectively lowers the risk of segmental renal infarction and worsening of hypertension compared with endovascular repair [10, 14]. It can also be used to address residual flow issues following endovascular repair [13, 15]. Unlike in situ surgical repair, which is challenging to perform in an environment with inflammatory adhesion, KAT extends the timeframe for surgical repair. It allows for microsurgical arterial reconstruction in a well-exposed, controlled setting, leading to a higher patency rate [13, 16]. However, according to Dezfouli's data, three kidney autotransplants experienced more intraoperative bleeding and postoperative complications than four patients each who underwent endovascular repairs and in situ surgical repairs [17]. Gwon et al. [6]divided a larger sample into three groups: 14 patients in the endovascular repair group, nine in the in situ surgical repair group, and 13 in the KAT group. At an average follow-up of 30.42 months, there were no statistically significant differences in the estimated glomerular filtration rate (eGFR) between the groups. Additionally, the KAT group showed no significant complications, while the endovascular repair group had three cases of renal infarction and one case of renal failure, and the in situ surgical repair group had one case of renal infarction.

KAT is a valuable procedure for complex renal artery stenosis, similar to its application in renal artery aneurysms. In a study conducted by Mhaske et al. [18], KAT was performed in nine carefully selected patients with renal artery stenosis and refractory hypertension in whom endovascular therapy was not a suitable option. Except for one patient who experienced a fatal myocardial infarction during the procedure, there were no adverse events. Additionally, the blood pressure and renal function levels of most patients improved compared to preoperative levels 2 years after the operation. After percutaneous endovascular renal angioplasty, renal artery restenosis is a common issue observed in 32.0% of patients over a mean follow-up period of 5.1 years [19]. KAT can serve as an effective treatment option for addressing this condition [20, 21]. In a study by Vijayvergiya et al. [21], KAT was performed in three patients who had previously undergone endovascular treatment but subsequently developed renal artery restenosis. This procedure resulted in the postoperative patency of the renal arteries. Furthermore, children [22] young patients [23], and patients with non-atherosclerotic stenosis [24] undergoing KAT for complex renal artery stenosis who did not respond to endovascular treatment also showed positive early and long-term outcomes.

The safety and efficacy of KAT have been demonstrated in the treatment of complex renal artery lesions. However, according to a systematic review by Contarini [13], the procedure has a major postoperative complication rate of 9.4%, with an autograft loss rate of 4.1%. Nevertheless, there were no hospitalization-related deaths or aneurysm recurrences during the follow-up period. A summary of clinical studies by Ramouz [25], covering KAT cases up to 2021, reported a postoperative complication rate of 6.9%, with no perioperative or follow-up deaths. The postoperative primary arterial patency rate was 90.8–100% for complex renal artery disease and ranged from 75 to 93% during 2–8 years of follow-up [10, 18, 26, 27]. KAT has shown promising results for the management of hypertension. Cure and remission rates for hypertension in patients who underwent this procedure ranged from 56.3–61.0% [7, 10, 25, 26]. In a study conducted by Li et al. [27] involving 16 patients with complex renal artery disease and hypertension, the average blood pressure significantly decreased from 150/87 mmHg before surgery to 128/77 mmHg 1 week after surgery ($P<0.05$). Additionally, the use of antihypertensive drugs significantly decreased after surgery ($P<0.05$). Another study conducted by Duprey et al. [10] examined 53 patients with renal artery disease complicated by hypertension. After a mean follow-up period of 8 years, the mean blood pressure decreased from 143/82 mmHg before the operation to 127/72 mmHg at the latest follow-up ($P<0.05$), and the mean number of antihypertensive drugs decreased from 2 to 0.94 ($P<0.05$).

Renal vein lesions

Nutcracker syndrome (NCS), also known as left renal vein compression syndrome, presents with common symptoms such as hematuria and pain [28]. It can be classified into anterior and posterior NCS based on the anatomical location of the left renal vein. Anterior NCS is more prevalent and occurs when the left renal vein is compressed between the abdominal aorta and superior mesenteric artery. Open surgery is the primary treatment for adult patients with NCS, with options including left renal vein transposition and KAT; transposition is often the preferred choice. Long-term follow-up is needed to assess the effectiveness of laparoscopic extravascular stent placement and radiointerventional endovascular stent placement for NCS [29]. Ali-El-Dein et al. [30] reported the successful treatment of anterior NCS using KAT, with all patients experiencing complete symptom relief. They suggested that KAT should be considered as a primary treatment option for anterior NCS. The use of KAT is more effective in normalizing left renal vein pressure because it resolves the left renal vein pull caused by left renal ptosis [31]. Additionally, KAT can be applied in cases of recurrent symptoms after left renal vein transposition [32]or recurrent symptoms after intravascular stent placement [33]. Reintervention within 2 years has a 32% probability in such cases [34]. Recently, Neppala et al. [35] reported the successful treatment of NCS using laparoscopic-assisted kidney autotransplantation (LAKAT) without the need for painkillers, as observed during a 1-year follow-up.

Ureteral diseases

Complex ureteral diseases are also important indications for KAT. In a retrospective study of autologous kidney transplant patients in the US Nationwide Inpatient Sample Database, Moghadamyeghaneh et al. [2] found that ureteral disease was the second most common indication with the lowest complication rate. They suggested KAT as an alternative procedure for treating complex ureteral diseases. Ureteral lesions often result from intrapelvic surgery, with incidence rates ranging from 1–10% [36]. The development and widespread use of ureteroscopic surgery have contributed to an increase in the incidence of ureteral lesions [37]. Patients with ureteral lesions often undergo multiple medical interventions [38], making the management of these lesions complex and challenging. KAT is a valuable option for addressing these difficulties. Ureteral avulsion, a rare yet severe injury affecting a long ureteral segment, is commonly treated with KAT [39–42]. Yakupoglu et al. [40] conducted a study of 12 cases of iatrogenic ureteral avulsion treated with KAT. Two patients required kidney removal owing to renal vein thrombosis, while the remaining patients exhibited satisfactory autograft function. With a mean follow-up time of 46.1 ± 31.7 months, the patient's eGFR at the last visit was 79.4 ± 20.6 ml/min. Bansal et al. [42] treated eight cases of ureteral avulsion using KAT. After a median follow-up of 11 years, no deterioration in renal function or significant complications were observed. Tonyali et al. [41] performed KAT in combination with Boari flap management in five patients with ureteral avulsion. The procedure yielded positive outcomes, with a low complication rate and no potential risk to renal function. Tran et al. [43] retrospectively analyzed 41 patients with complex ureteral strictures who underwent LAKAT. These strictures were mostly caused by iatrogenic injuries during urinary tract stone surgery. The average length of the stenosis was 4 cm, and most strictures were found in the upper ureter. After an average of 63 months of follow-up, three patients underwent autograft nephrectomy, while the remaining four patients experienced complications. Roux et al. [38] reported satisfactory results in eight KATs and 14 ileal ureter substitutions for long ureteral strictures. No differences in renal function were observed before and after surgery or between the two treatment modalities. In addition to KAT and ileal ureteral surgery, other surgical methods, such as endoscopic therapy, ureteral-ureteral anastomosis, ureteral bladder reimplantation, psoas hitch ureteroneocystostomy, Boari bladder valve ureteral surgery, buccal mucosa grafting, and appendix interposition, can also be considered based on the location and extent of ureteral damage. In particular, the popularization of buccal mucosal grafting has facilitated the complex reconstruction of the ureter [44]. KAT serves as an alternative to other surgical methods and is a suitable option for managing complex ureteral lesions, particularly those involving the upper or long segments of the ureter [45, 46].

Tumors

Radical and partial nephrectomies are considered curative treatments for localized renal cancer. Partial nephrectomy is recommended for patients with T1aN0M0 disease because it offers better preservation of renal function, improved quality of life, and increased life expectancy [47]. The preservation of the nephrons and avoidance of renal replacement therapy have also led to the consideration of KAT in cases of renal tumors, particularly complex renal tumors that cannot be removed in situ while preserving the organs, such as central renal tumors or tumors involving the renal hilum. Using KAT, Abraham et al. [48]successfully treated three complex renal tumors, two of which were complex renal cancers. Only one patient with a solitary kidney required temporary hemodialysis after surgery, while the others did not develop complications. Zhu et al. [49] reported four patients who underwent KAT for central-type renal tumors. One patient required graft removal owing to renal atrophy 6 months post-surgery, but the remaining graft continued to function effectively. However, the potential of KAT to increase the risk of malignant renal tumor recurrence is controversial, thereby limiting its application. One Oxford study reported a 5.4% recurrence rate within 10 years of KAT in 37 patients with stage T3 renal cancer. At the 10-year mark, the overall graft and patient survival rates were 82% and 75%, respectively, in 50 patients [50]. Tran et al. [43] conducted a retrospective study of eight patients who underwent LAKAT for renal malignancies. Of the eight patients, seven had highly complex central renal tumors, and four had solitary kidneys. Although all surgical margins were negative, 50% of the patients experienced relapse after surgery. A literature review by Ruiz et al. reported a tumor recurrence rate as high as 25–50% for complex renal cell carcinoma treated with KAT [45]. However, the non-cancerous nature of benign kidney tumors supports the use of nephron-sparing surgery. Renal angiomyolipoma, a prevalent benign renal tumor, demonstrated favorable outcomes when KAT was employed in cases of inferior vena cava tumor embolism, as reported by Chen et al. [51].

In cases of urothelial carcinoma affecting the renal pelvis or ureter, particularly when both kidneys are affected or when only one kidney is present, KAT can be considered a viable option [52, 53]. Holmäng et al. [54] conducted a long-term follow-up study spanning 7–20 years in 23 patients with upper tract urothelial carcinoma who underwent KAT. They concluded that KAT may benefit patients with upper tract urothelial carcinoma who have only one kidney. Janssen et al. [55] reported no instances of relapse at the 5-year follow-up among five patients with a solitary kidney who underwent KAT for upper urinary tract urothelial carcinoma. Steffens et al. [56] reported four cases of urothelial carcinoma of the upper urinary tract in patients with solitary kidneys. The study found no postoperative complications or abnormalities in renal function. Furthermore, there were no instances of tumor recurrence during the 6–14 years of follow-up, and all four patients remained alive. Cheng et al. [52] treated 12 patients with KAT and reported no severe complications or renal function abnormalities, except for one patient with a solitary kidney who required temporary dialysis. The researchers conducted meticulous endoscopic follow-ups and managed to remove small recurrent lesions in three patients through transurethral resection. Furthermore, there are limited reports on the utilization of KAT in the management of bilateral Wilms' tumors [57], particularly in cases involving highly complex bilateral Wilms' tumors that affect the renal sinus [58]. However, with the advancements in robotic surgery, the need to perform bench surgery for tumor excision and renal repair is exceptionally rare so this would be a very rare use of KAT in the current era. It might be worthwhile to stress that this would be a technique of last resort in the modern era of minimally invasive nephron sparing surgery.

KAT has also been explored as a therapeutic approach for retroperitoneal tumors surrounding the kidneys or ureters. These tumors often necessitate complete mass removal. In many cases, this entails the simultaneous removal of the closely attached kidney and ureter. Subsequently, the excised kidney can be preserved through KAT. Bradley et al. [59] observed that a significant proportion (50.2%) of cases involving complete resection of retroperitoneal tumors required the removal of adjacent organs. The most commonly excised structures were the kidney, ureter, and large intestine. Remarkably, even though 20% of patients who underwent resection of retroperitoneal sarcoma simultaneously underwent nephrectomy, pathological examinations revealed that 73% of the kidneys were not invaded by the tumor [60]. These findings partially support the application of KAT for retroperitoneal tumor resection. Good renal function and oncological results have been reported in KAT for retroperitoneal liposarcoma [61], adrenal neuroblastoma [62], mixed germ cell tumors [63, 64], and gangliocytomas [65]. However, it is important to note that certain studies have highlighted an elevated risk of complications. In a large-sample study conducted by Moghadamyeghaneh et al. [2], the use of KAT for the treatment of malignant renal tumors or malignant tumors involving the kidneys resulted in complications in 47.5% of patients, with 12.3% of patients experiencing transplant renal failure.

Loin pain-hematuria syndrome

Loin pain-hematuria syndrome (LPHS) is a rare medical condition and an uncommon indication for KAT. Patients often experience severe, unexplained, and chronic unilateral or bilateral lumbar pain associated with macroscopic or microscopic hematuria, as first reported by Little et al. [66]. Given the lack of consensus regarding the underlying pathological mechanisms and etiology of LPHS, there are diverse treatment options for managing this condition. These options encompass the use of angiotensin-converting enzyme inhibitors or angiotensin II receptor blockers [67], pain medication administration [68], intraureteral injection of bupivacaine [69], renal denervation [70], radiofrequency ablation [71], and KAT [46, 72–74]. There is also a dearth of high-level evidence favoring one strategy over another in the treatment of LPHS. Some studies have indicated that 25–50% of patients with LPHS may experience spontaneous remission within 3–5 years [75]. Therefore, adopting a progressive treatment approach, starting with conservative measures and progressing towards invasive interventions, is often considered a reasonable strategy. Surgical indications should include patients who require high doses of analgesics to control pain and those for whom non-surgical treatments have proven ineffective [72]. Notably, at the Cleveland Clinic, 16 patients with LPHS underwent KAT, and a marked reduction in pain was observed in 75% of these individuals based on pain scores recorded 30 days post-surgery [76]. KAT is a viable option for patients who experience recurrent pain despite undergoing other treatments. Sheil et al. [77] reported that three out of four patients who experienced recurrent pain following renal denervation were successfully treated with KAT. However, it is worth noting that pain recurrence after KAT has been observed, with a meta-analysis conducted by Coffman reporting a recurrence rate of 37.5% [78]. Pain recurrence after KAT usually occurs within 2 years of surgery [79]. Some scholars have proposed that this recurrence may be related to nerve reinnervation and have advocated for intraoperative anastomosis following severing of the ureter. They believe that this approach reduces the risk of autonomic nerve reinnervation or incomplete denervation [32]. To address the issue of pain recurrence following KAT, certain researchers have introduced the "UW-LPHS trial" [32, 80] and renal hiltal block [81] to assess the potential benefits for patients undergoing KAT.

Solitary or bilateral kidney disease

When individuals with either a solitary kidney or both kidneys are affected by complex kidney-related diseases, such as ureteral avulsion in a patient with a solitary kidney or bilateral complex renal artery aneurysms affecting both kidneys, KAT can be considered as a highly advantageous approach. This is primarily due to its ability to preserve nephrons and maintain renal function, offering a superior alternative to nephrectomy.

Morin et al. [82] conducted KAT in nine patients with solitary kidneys. In this cohort, all patients experienced a temporary increase in serum creatinine levels postoperatively but achieved full recovery within 4–10 days. Remarkably, their renal function remained stable at baseline throughout the mean follow-up period of 89 months. Similarly, Gwon et al. [6] performed KAT in nine patients with solitary kidney disease. One patient unfortunately died during the perioperative period owing to multiple cerebral embolisms. Except for one patient with renal cell carcinoma, the eGFR of the remaining patients did not exhibit a significant decrease 1 year after surgery. Nayak et al. [83] managed three cases of complex renal cancer involving the renal hilum of solitary kidneys using LAKAT. All patients maintained stable renal function during the 39-month follow-up period following the surgery. In another study by Ju et al. [84], LAKAT was employed to treat three cases of renal cell cancer involving solitary kidneys and three cases involving both kidneys. Among these patients, two required temporary hemodialysis after surgery. However, during the follow-up period, all patients exhibited a mean serum creatinine level of less than 200 μmol/L and did not necessitate further hemodialysis. Tragically, one patient died 18 months after surgery owing to multiple metastases, but the five remaining patients were alive and free from tumor recurrence.

The common indications mentioned above are illustrated in Fig. 2. Other uncommon indications for KAT are shown in Table 1.

Advances in technology

Traditional KAT is performed using an open surgical procedure. The process begins with the removal of the diseased kidney, followed by its trimming on the workbench under controlled conditions at a temperature of 4 °C. Subsequently, the repaired kidney is surgically reimplanted ectopically into the iliac fossa. During this procedure, the renal arteriovenous system is primarily connected to the iliac vessels, while the renal ureter is re-anastomosed to the bladder. Therefore, compared with other surgical procedures, KAT presents risks of potential short- or long-term complications that may arise following vascular and urinary tract anastomosis. Additionally, some surgeons choose not to sever the ureter but instead reconnect the renal blood vessels with the aorta and vena cava following extracorporeal repair of the kidney, and subsequently place the kidney back into

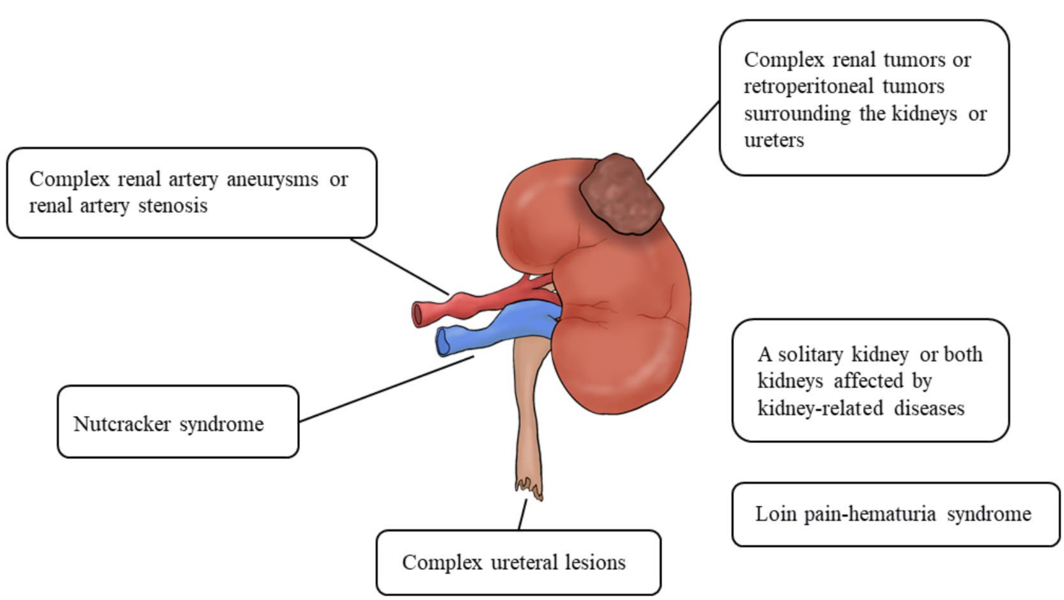
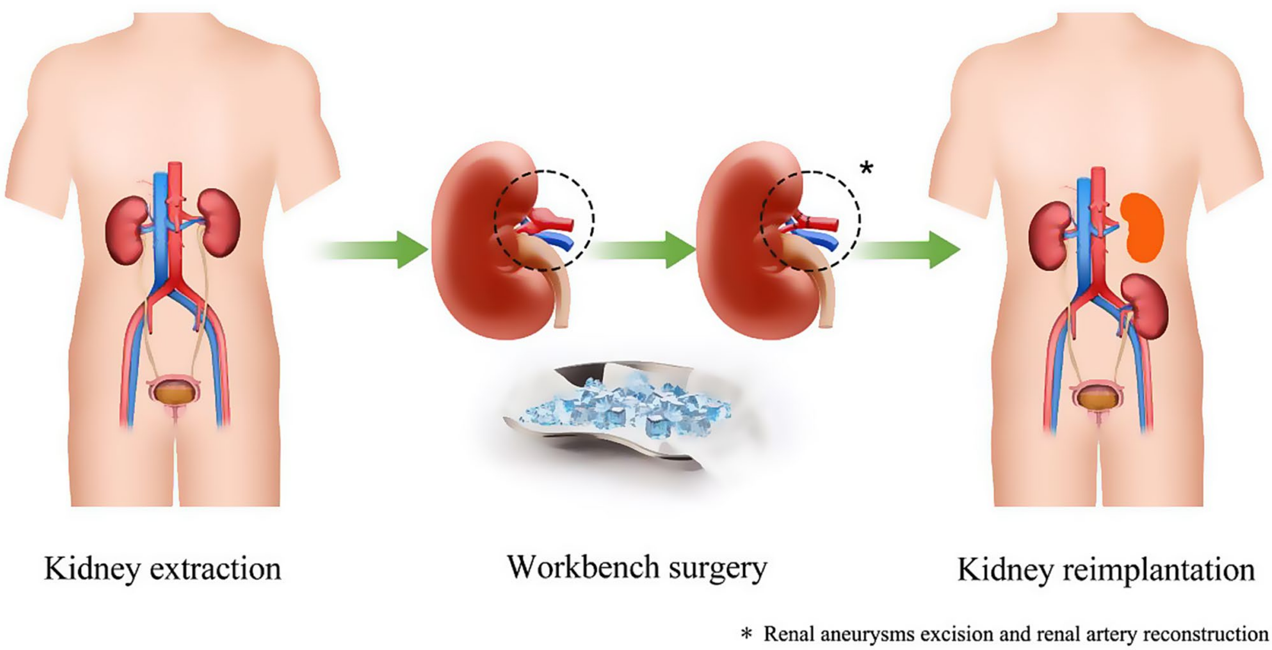


Fig. 2 Common indications for kidney autotransplantation

Table 1 Other uncommon indications for kidney autotransplantation

First author	Year of publication	Indications
Hanlon [85]	2020	Aneurysm-like dilation of the great saphenous vein used to reconstruct the renal artery during kidney transplantation 21 years ago
Bourgi [86]	2018	The living donor kidney was reimplanted into the donor because the recipient had perioperative heart failure
Rana [87]	2012	The aortic aneurysm involves the origin of the renal artery in the functional right solitary kidney
Bölling [88]	2009	To prevent radiation exposure of the left kidney, it was shifted away from the radiation field
Ghidini [89]	2021	Transplanted renal vein thrombosis after renal transplantation
Morosanu [90]	2021	Dissecting aneurysm of renal artery
Kim [91]	2021	Middle-aortic syndrome involving the renal artery
Flechner [92]	2011	Refractory metabolic stones



		Indications	Ureter management	Renal vascular management	Location of kidney replantation
Orthotopic kidney autotransplantation		Renal vascular lesions	Keeping the ureter intact	Reconnecting the renal blood vessels with the aorta and vena cava	Renal fossa
Alterotopic kidney autotransplantation	Open Laparoscopic-assisted In vitro robotic-assisted In vivo robotic-assisted	Renal vascular lesions、Ureteral diseases、Tumors、Loin pain-hematuria syndrome	Disconnecting or not disconnecting the ureter as appropriate	Reconnecting the renal blood vessels with iliac vessels	Iliac fossa

Fig. 3 Flowchart of kidney autotransplantation

its original renal fossa [23, 93]; this procedure is known as orthotopic KAT. Orthotopic KAT circumvents potential complications associated with ureterocystostomy but is primarily utilized in cases involving renal vascular lesions. However, this procedure involves partial clipping of the aorta during anastomosis, which has a more significant hemodynamic impact than the partial clipping of the iliac vessels. Alterotopic KAT is a widely used method (Fig. 3). Nevertheless, anastomosis and perfusion of the renal arteries may not be ideal in cases involving iliac vascular lesions, such as atherosclerosis. Consequently, KAT is relatively contraindicated in patients with severe iliac vascular disease or retroperitoneal fibrosis affecting the iliac vessels. An important contraindication of KAT is insufficient residual renal function in the affected kidney, which may be defined as a split eGFR < 20 or 15 mL/

(min/1.73 m²) [52, 94]. In other words, if kidney function is severely compromised or minimal, KAT may not be a suitable treatment option.

With the advancement of minimally invasive surgical techniques, KAT is increasingly performed using these techniques. Conventional KAT has drawbacks, such as significant trauma and a longer postoperative hospital stay. However, Ramouz et al. revealed that LAKAT results in a shorter postoperative hospital stay than open KAT [25]. Fabrizio et al. [95] described the first case of LAKAT involving laparoscopic nephrectomy, workbench surgery, and open kidney transplantation. They successfully treated a patient with a mucosal avulsion of the proximal ureter. Later, the use of LAKAT expanded to include conditions such as LPHS [96], renal artery aneurysms [97], and renal tumors [84]. Tran et al. [43] conducted a retrospective study involving the largest cohort of patients who underwent LAKAT ($n = 52$). The primary indications for surgery were ureteral strictures and renal malignancy. After an average follow-up of 73.5 months, 90% of the patients retained autograft function. Complications occurred in 15% of the patients, but there were no Clavien–Dindo grade IV or V complications, and no deaths directly attributed to the surgery. Their study provided strong evidence of the safety and long-term effectiveness of LAKAT. An increasing number of scholars believe that laparoscopic nephrectomy, workbench surgery, and open kidney transplantation should be considered the gold standards for KAT. To further minimize the incision and trauma, Cui et al. [98] successfully performed LAKAT in vivo using a 3D-printed kidney cooling sleeve. The kidney did not need to be removed from the body; all procedures, including trimming of renal vessels, anastomosis, and cold perfusion, were performed in vivo.

Hoznek et al. [99] achieved a significant milestone by performing the first robotic-assisted kidney transplantation. Following this breakthrough, Gordon et al. [100] successfully performed the first case of robotic-assisted kidney autotransplantation (RAKAT), which was conducted to address a long segment of ureteral necrosis. Furthermore, Lee et al. [101] developed techniques to shorten the ischemic time. However, these studies used intracorporeal robotics to treat ureteral diseases. Extracorporeal RAKAT requires the use of a GelPOINT device to extract the affected kidneys during workbench surgery. Yao et al. [102] expanded the application of RAKAT to include complex renal artery aneurysms. They operated by making A Pfannenstiel incision to insert the GelPOINT device, along with six small ports. However, this method requires multiple ports. Kaouk et al. [103] reported their experience with a periumbilical single-port robotic platform, completing three cases of autologous kidney transplantation and six cases of allogeneic kidney transplantation. In these cases, the kidneys were repaired in vitro using the GelPOINT device, and ideal postoperative recovery and renal function were observed. Thus, the single-port robotic platform holds promise for reducing postoperative complications. They later summarized eight cases of RAKAT using the same procedure, with no postoperative complications or graft function loss, stable renal function, and improved back pain symptoms [104]. This approach would be ideal in terms of minimizing patient morbidity and likely represents the future of RAKAT. In a study by Decaeestecker et al. [105], seven patients received extracorporeal or intracorporeal RAKAT for benign diseases. One case of Clavien–Dindo grade > II complications occurred after the operation, and the median hospitalization time was 5 days. No discomfort or abnormal renal function was observed 3 months after surgery. Among 29 patients with benign disease in Breda's study [94], 15 underwent extracorporeal RAKAT, while 14 underwent intracorporeal RAKAT. Intracorporeal RAKAT had shorter cold ischemia and total ischemia durations, but extracorporeal RAKAT showed faster recovery of transplanted kidney function. With a total complication rate of 34.4% within 90 days after surgery, the Clavien–Dindo > II was 13.8%. A renal function level similar to the preoperative level was observed 1 year after surgery. The study by Mejia et al. represents the largest cohort of RAKAT to date [106], with 32 patients who underwent intracorporeal RAKAT: three with LPHS and 29 with NCS. All patients successfully completed the RAKAT procedure, with 63% showing complete improvement in pain symptoms, 50% experiencing complications, 6% of graft failure, and no deaths during a mean follow-up of 10.9 months. Overall, RAKAT results in smaller surgical scars and a faster postoperative recovery [107]. Other literature for RAKAT is summarized in Table 2. However, there are still not enough documented cases, with the majority involving benign primary conditions. Additional investigations are required to assess the long-term results in patients receiving RAKAT.

Conclusion

Currently, KAT is often considered an elective treatment option for renal vascular lesions, ureteral diseases, tumors, and loin pain-hematuria syndrome. It has an accurate effect and is the final treatment method for patients requiring kidney preservation, particularly those with conditions affecting a solitary kidney or both kidneys. On the technical front, LAKAT has demonstrated both safety and efficacy. The application of the robotic surgical systems have yielded satisfactory results in KAT. Currently, the primary focus of the advancement of KAT techniques is to minimize surgical trauma. However, it is important to note that research in the field of KAT predominantly consists of case series and retrospective

Table 2 Summary of literature for robot-assisted kidney autotransplantation

First author, Year of publication	Indications	No. of cases	Type of surgical procedure	No. of ports	Warm ischemia time (min)	Cold ischemia time (min)	Operative time (min)	EBL (mL)	LHS (d)	Follow up (mth)	No.of compli-cations	Creatinine(mg/dL)	Symptoms
Gordon, 2014 [100]	Ureteral loss	1	In vivo	5	2.3	95.5	425	50	1	5	0	0.95	-
Lee, 2015 [101]	Ureteral stricture	1	In vivo	-	4	48	390	400	5	3	2	-	-
Mejia, 2023 [106]	LPHS, NCS	32	In vivo	4	-	77.5	234	-	4.5	10.9	16	0.83	63% of population experiencing complete improvement in pain symptoms
Yao, 2020 [102]	Renal artery aneurysm	1	In vitro	7	-	-	-	-	6	12	0	0.68	Blood pressure remained stable without drugs
Kaouk, 2023 [104]	Chronic visceral pain, Ureteral disease	8	In vitro	1	6	130.5	519.5	100	3	13	1	0.95	Near complete resolution of pain scores
Decaeestecker, 2018 [105]	Ureteral stricture, NCS, LPHS	7	Both	5–6	2	178	370	60	5	3	3	0.80	Free from flank pain and hematuria
Breda, 2022 [94]	Ureteral stricture, Renal artery aneurysm, NCS, LPHS	29	Both	6–7	3	108	350	110	5	12	10	0.84	-

EBL: Estimated blood loss; LHS: Length of hospital stay studies, lacking higher levels of evidence. Despite these limitations, KAT remains a valuable and increasingly refined therapeutic option for patients with complex renal conditions requiring kidney preservation.

Abbreviations

KAT	Kidney autotransplantation
eGFR	Estimated glomerular filtration rate
NCS	Nutcracker syndrome
LAKAT	Laparoscopic-assisted kidney autotransplantation
LPHS	Loin pain-hematuria syndrome
RAKAT	Robotic-assisted kidney autotransplantation
EBL	Estimated blood loss
LHS	Length of hospital stay

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Author contributions
S.J.L.and J.G.contributed equally to this work and should be considered co-first authors. S.J.L.and J.G.designed the study, wrote the main manuscript text. S.H.,Y.H.and D.H.prepared Figs. 1, 2 and 3. S.H.L.and Y.L.prepared Table 1 and 2. J. Q.,J.L.andC.X.W.contributed to revised the manuscript for important intellectual content.C.L.W.supervised the entire project, secured funding, and reviewed the final manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

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Not applicable.

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The authors declare no competing interests.

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