Review

Special Topic: Advances in Treatment of Renal Carcinoma

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# Robotic surgical techniques and methods for treating renal cell carcinoma with inferior vena cava tumor thrombus

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## Abstract

Renal cell carcinoma with inferior vena cava (IVC) tumor thrombus (RCC-IVCTT) has a high mortality rate, and surgery is the only promising treatment. Open surgery has been the gold standard treatment for several decades. However, with the development of minimally invasive surgical technologies, the advantages of robotic surgery have gradually emerged. The classic Mayo Clinic Classification system has certain limitations in guiding robotic surgery. Therefore, a new classification system that is compatible with robotic surgery is urgently needed. Advancements in robotic surgery must be systematically summarized and evaluated. Since Abaza's initial report on robotic surgery, the exploration of robotic radical nephrectomy (RRN) with IVC thrombectomy has resulted in numerous related techniques and approaches, including surgical positions and approaches, control of blood vessels, assisted exposure, step-by-step strategy, and preoperative and intraoperative auxiliary technology and equipment. Our team proposed a new tumor thrombus classification system termed the “301 Classification” based on RRN with venous thrombectomy, which matches each level of tumor thrombus with a distinct robotic surgical strategy. With advances in technology and accumulated experience, RRN with IVC thrombectomy holds promise as the preferred surgical option for RCC-IVCTT. Although “301 Classification” can provide objective advantages in robotic surgery, more cases are needed to be optimized for guiding surgery accurately. The overview provided in this paper aims to serve as a reference and inspiration for future research and clinical practice regarding RCC-IVCTT.

**Keywords:** Renal cell carcinoma; Tumor thrombus; Inferior vena cava; Nephrectomy; Thrombectomy; Robotic surgery; Classification system

## 1. Introduction

Renal cell carcinoma (RCC) with inferior vena cava (IVC) tumor thrombus (RCC-IVCTT) is one of the most challenging urological diseases. Traditional open radical nephrectomy (RN) with IVC thrombectomy has long been the guideline-recommended standard since the first successful case was reported seminally by Skinner et al.[1] In recent decades, minimally invasive surgical techniques have rapidly evolved and gradually been introduced into various urological subspecialties. After 2002, sequential reports emerged on the hand-assisted laparoscopic approach, hybrid laparoscopic-open approach, and pure laparoscopic approach for RN and tumor thrombectomy.[2–4] Despite these advancements, widespread adoption has been hindered by the demanding technical requirements inherent to laparoscopic procedures for both surgeons and assistants.

In 2011, Professor Ronney Abaza[5] introduced an initial series of robotic surgeries for RCC-IVCTTs. Compared with open and laparoscopic approaches, robotic surgical systems offer several advantages, including 3-dimensional (3D) vision controlled by the surgeon, 360-degree rotating and retractable arms, and a stable and ergonomic platform. Since then, urologists worldwide have begun to explore this minimally invasive approach, with an emerging tendency to gradually replace open surgery.

Over the past decade, the development of robotic RN (RRN) with IVC thrombectomy has spawned numerous techniques and approaches tailored to robotic surgery. Two recent narrative reviews[6,7] summarized the surgical strategies of RCC-IVCTT at different levels, comprehensively reviewed the studies on the treatment of RCC-IVCTT at all levels by robotic surgery, focused on the outcome indicators of each study, made an objective discussion on preoperative preparation, demonstrated the intuitional benefits of robotic surgery, and provided important guidance for the surgical decision-making of patients with RCC-IVCTT. Several studies have summarized and evaluated robotic surgery from 1 or 2 perspectives.[8,9] However, the summary of the techniques and approaches for robotic surgery is not comprehensive and detailed enough. This review aims to address this gap by summarizing, analyzing, and comparing the advantages and disadvantages of each advancement in relevant techniques and

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approaches. Thus, it seeks to provide readers with a comprehensive understanding of the current state of development in this field and offers guidance on robotic surgical skills.

## 2. Materials and methods

We conducted an extensive literature search of PubMed, covering articles published from the inception of the database until April 1, 2024. Only publications in English were included. We employed Medical Subject Headings terms using Boolean operators (AND, OR, NOT), including "Kidney Neoplasms," "Renal Veins," "vena cava, inferior," "Robotic Surgical Procedures," "Minimally Invasive Surgical Procedures," "Laparoscopy," and "Robotics." The detailed search strategy is shown in Table 1. Of the 56 retrieved articles, one written in Latin was excluded.

## 3. The classification of renal cell carcinoma with inferior vena cava tumor thrombus

The RCC-IVCTT classification significantly guides surgical treatment. In 1987, Neves and Zincke[10] retrospectively analyzed data from 54 cases of RCC with venous tumor thrombus (TT) treated by surgeries at the Mayo Clinic, proposing the initial classification system of TT ("Neves-Zincke" classification) (Fig. 1C). Building upon this, Ciancio et al.[11] refined the definition of level III TT, delineating it into 4 subcategories (IIIa–IIId), thus forming the University of Miami's experience (Fig. 1D). In 2004, Blute et al.,[12] also from the Mayo Clinic, retrospectively reviewed data from 540 patients with venous TT who underwent surgeries at their institution and then modified the "Neves-Zincke" classification to create the most widely utilized Mayo Clinic Classification system (Fig. 1A), which is defined as follows: The level of TT that is limited to the renal vein (RV) is classified as 0, the one that extends less than or equal to 2 cm above the RV is classified as I, the one that extends more than 2 cm above the RV but below the hepatic veins is classified as II, the one that extends above the hepatic veins but below the diaphragm is classified as III, and the one that extends above the diaphragm is classified as IV. However, the Mayo Clinic Classification is based on open RN with IVC thrombectomy and may not be fully applicable to robotic approaches. A previous study from our team made an analysis of 100 cases of RRN with venous thrombectomy from 2013 to 2017, resulting in the development of a new original TT classification system termed the "301 Classification" (Fig. 1B).[13,14] With the promotion in recent years, the classification system has been gradually improved and accepted by more and more general hospitals in China. This new system aligns each TT level with a distinct robotic surgical strategy, and most surgical techniques and approaches in this review are classified according to the system to be introduced. The comparison of the four classification is listed in detail in Table 2.[10–14] And the conclusions of our experience with the 301 Classification system are listed in Supplementay Table 1 (http://links.lww.com/CURRUROL/A72).

## 4. Robotic surgical techniques and approaches categorized according to the "301 Classification"

### *4.1. Level 0 ("301 Classification")*

Because the left RV is much longer than the right RV and transcends the aortic artery and superior mesenteric artery, our institution proposed the difference between the left and right sides of RCC-IVCTT and divided the right side of level 0 TT into levels 0a and 0b according to the "301 Classification."[15,16] For right-sided level 0 and left-sided level 0a cases, only RRN needs to be performed. In the right case, Abaza[5] initially placed the patient in the left lateral decubitus position (LDP) at 90 degrees to perform robotic surgery, whereas Gill et al.[17] in 2015 used a new right side up, 60-degree lateral position. Our team modified the surgical position to the left LDP using a 70-degree bump (Fig. 2A).[16] Ramirez et al.[18] also used a similar position with 60-degree table flexion at the level of the anterior superior iliac spine (Fig. 2B). This modified position has been adopted by several investigators.[19]

For left-sided level 0b cases, after preoperative angioembolization, the left RV was ligated at the point of IVC insertion in a modified left LDP with a 70-degree bump; the patient was subsequently repositioned to proceed with RRN, and the procedure was the same as level 0a TT.

This repositioning method was first proposed by our team in 2016,[16] which is equally practical for left RCC-IVCTT beyond level 0b. Based on the experience of our team, Li et al.[20] changed the surgical sequence. Left-sided RN was first performed; the left RV was only mobilized but not disconnected, the thrombus was pushed into the left RV, and thrombectomy was performed, which proved its feasibility in patients with left RCC with level I IVCTT. Nelson et al.[21] also used a similar position conversion to treat IVCTT extending below the hepatic veins.

### *4.2. Level I ("301 Classification")*

***Methods for controlling key blood vessels*** Important blood vessels during RCC-IVCTT include the IVC, renal arteries (RAs) and veins, lumbar veins, gonadal veins, right adrenal veins, and short hepatic veins (SHVs). Ensuring that these blood vessels are controlled is crucial for the success of the operation. The methods for vascular control in level I TT are summarized below and are also applicable to cases that extend to higher levels.

(1) **Cross-clamping of the inferior vena cava**

**Table 1**

**Detailed search strategy for the review.**

| Items | Specification |
|---|---|
| Date of search | April 1, 2024 |
| Databases we searched in | PubMed |
| Searching by Medical Subject Headings | (("Robotics"[MeSH Terms] AND ("Minimally Invasive Surgical Procedures"[MeSH Terms] OR "Laparoscopy"[MeSH Terms])) OR "Robotic Surgical Procedures"[MeSH Terms]) AND ("Kidney Neoplasms"[MeSH Terms] AND ("Renal Veins"[MeSH Terms] OR "vena cava, inferior"[MeSH Terms])) |
| Timeframe | From the inception of the database to April 1, 2024 |
| Inclusion and exclusion criteria | 1) English literatures including case reports, comments and editorials, retrospective studies, clinical trials, reviews and systematic reviews<br>2) The subject is about robotic approaches in the treatment of renal cell carcinoma with inferior vena cava tumor thrombus |
| Selection process | Jin Luo, Zhuoran Li, Qiwei Liu, Yuqi Jia, and Jinqiao Li collected the literatures and extracted the relevant information. All authors jointly discussed and selected the targeting literatures for the review. |

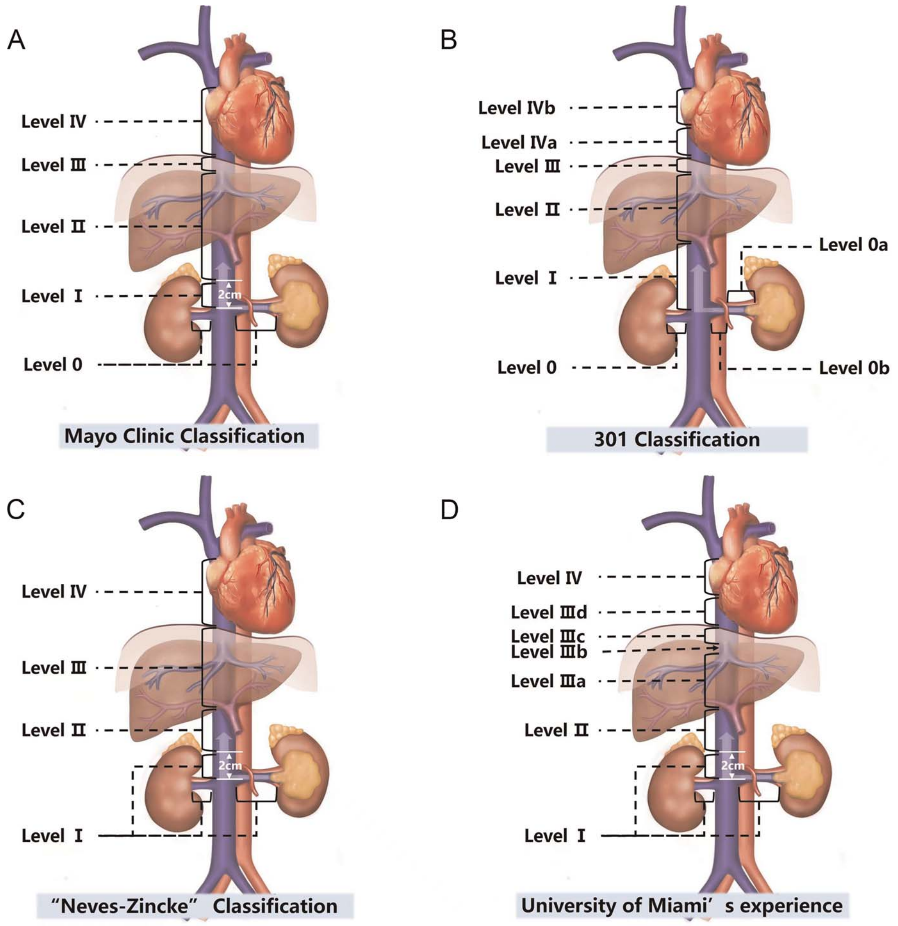


**Figure 1.** Anatomical diagram of different classification systems for renal cell carcinoma with inferior vena cava tumor thrombus. (A) The Mayo Clinic Classification. (B) The "301 Classification." (C) The "Neves-Zincke" classification. (D) The University of Miami's experience.

In 2011, Abaza[5] reported an initial series of RRN that underwent IVC thrombectomy. Subsequently, research on robotic surgery to treat TT began to increase worldwide and replicated the cross-clamping step in open surgery using minimally invasive techniques and confirmed its feasibility. In brief, a modified Rommel tourniquet was fashioned with vessel loops placed twice around the cephalic and caudal IVC and contralateral RV, and robotic Hem-o-Lok clips were used to cinch and secure the tourniquet. This is of great significance, because subsequent researchers have adopted this important technique individually, some of whom have made changes based on local conditions.

(2) **Tangential clamping of the inferior vena cava with a laparoscopic Satinsky clamp**

Abaza[5] explained the use of the Satinsky clamp for a patient who could not tolerate IVC cross-clamping because of severe aortic stenosis. The specific steps are as follows: Using a curved laparoscopic Satinsky clamp, the IVC containing the TT was clamped tangentially. The wall of the IVC was incised along the inner curvature of the Satinsky clamp, and the TT was completely removed. Finally, the incision of the IVC was sutured beneath the clamp by using 4-0 polypropylene. However, the application conditions of this technology are relatively limited, and the extension range of the tumor within the IVC lumen should not be too large. Thus, it is only appropriate for certain easy cases of level I TT.

(3) **Double blocking by cross-clamping and bulldog clamps**

To ensure that the blood flow inside the IVC is absolutely blocked, Motoyama et al.[22] and Takahara et al.[19] clamped IVC and RVs with twice-wrapped vessel loops and bulldogs. However, most studies use a single technique, cross-clamping, to obtain vessel control. Dual blocking may be beneficial in complex cases with a high risk of bleeding.

(4) **Split-and-roll techniques**

Sandberg et al.[23] used the adventitia of the IVC as a plane of dissection and carefully identified all tributaries of the IVC, including the lumbar veins, gonadal veins, right adrenal veins, and SHVs, to minimize the risk of vascular injury. They concluded that the split-and-roll technique is a safe surgical option for young urologists who do not have much experience in robotic surgery for dissecting the IVC branches.

(5) **Detection of the control effect of inferior vena cava**

Before starting the main step of thrombectomy, operators can make a small incision in the blocked segment of the IVC or in one of the gonadal vein stumps to check whether all lumbar veins are fully controlled.[5,24] Gill et al.[17] used laparoscopic Doppler ultrasound exploration or needle aspiration for complete detection. Similarly, Ramirez et al.[18] described an approach using an

**Table 2**

**Comparison of different classification systems for RCC-IVCTT.[10–14]**

| The name of classification systems<br>Anatomical landmark location | Mayo Clinic Classification | 301 Classification | "Neves-Zincke" classification | University of Miami's experience |
|---|---|---|---|---|
| TT limited to the RV, not beyond the SMA (left-sided) | 0 | 0a (left-sided) | I | I |
| TT limited to the RV, beyond the SMA (left-sided) | | 0b (left-sided) | | |
| TT extending ≤2 cm above the RV | I | I | | |
| TT extending >2 cm above the RV but below the FPH | II | | II | II |
| TT extending above the FPH but below the hepatic veins | | II | III | IIIa |
| TT located in the orifice of the hepatic vein of IVC (SPH) | | | | IIIb |
| TT extending above the SPH but below the diaphragm | III | III | | IIIc |
| TT extending above the diaphragm but outside the atrium | IV | IVa | IV | IIId |
| TT extending into the atrium | | IVb | | IV |

FPH = first porta hepatis; IVC = inferior vena cava; RCC-IVCTT = renal cell carcinoma with inferior vena cava tumor thrombus; RV = renal vein; SMA = superior mesenteric artery; SPH = second porta hepatis; TT = tumor thrombus.

18-gauge laparoscopic needle inserted into the IVC in their case report the following year. We believe that this procedure should be considered in all thrombectomy cases. Although it increases the number of surgical steps, it can also reduce intraoperative blood loss.

***Vascular blocking and releasing sequences*** In addition to the methods used to achieve vascular control, the blocking and release sequence of target vessels is also an issue worthy of discussion.

Some investigators blocked the caudal IVC, contralateral RV, and cephalic IVC in that order,[16,19,25] whereas others blocked the cephalic IVC, contralateral RV, and caudal IVC in that order[24]; others obtained vascular blocking of the contralateral RV, caudal IVC, and cephalic IVC in that order.[18,22] The first measure seems to be more consistent with the direction of venous return, that is, from distal to proximal vessels. Blocking the cephalic IVC may seem unconventional; however, it can reduce the risk of intraoperative vascular embolism. In 2012, Lee and Mucksavage[24] proposed that the caudal IVC tourniquet should loosen first before the IVC is sutured completely to test the closure and vent any clot or debris within the IVC, whereas our team took measures in which the vessel loops of the cephalic IVC, right RV, and caudal IVC were loosened in order.[16] Theoretically, releasing the caudal IVC first can reduce the incidence of pulmonary embolism to some extent, but releasing the cephalic IVC first can reduce bleeding caused by inaccurate suturing. In addition, patients with left RCC-IVCTT are also involved in blocking the right RA, which usually precedes RV blocking, taking into account the postoperative renal dysfunction caused by renal congestion.

***Lateral kidney retraction*** Abaza[5] used a robotic arm to retract the lateral kidney and shorten the tumor in the IVC lumen. For more extensive TTs, it is possible to change the surgical approach through this operation, such as by meeting the conditions for using a laparoscopic Satinsky clamp. Before performing this procedure, it should be ensured that the kidneys are completely free.

***The liver retraction without mobilization*** Our team summarized the main points and characteristics of robotic surgery for treating patients whose proximal thrombus was inferior to the first porta hepatis (FPH) or between the FPH and the second porta hepatis (SPH).[26] In conclusion, for IVCTT inferior to the FPH, the liver is retracted upwards by a nondestructive laparoscopic clamp placed in the assistant port, and some SHVs are ligated without mobilizing the liver throughout (Fig. 3A). Although these thrombi are classified as level II according to the Mayo Clinic Classification, no new techniques have been used compared to Mayo level I IVC thrombi. Consequently, they suggested an IVCTT between the RV's ostium and FPH could be reclassified as "new level I."[16] For proximal thrombi between the FPH and SPH, the main points of the operation are described in the next section.

### 4.3. Level II ("301 Classification")

***Position and approach*** For a proximal thrombus between the FPH and SPH, the right lobe of the liver needs to be mobilized; therefore, the surgical procedure is different from that mentioned above, even for the patients' positions. A 30- to 40-degree dorsal elevated lithotomy position and the 5 ports (Fig. 3B) were taken to accomplish liver mobilization, the brief steps of which were disconnecting the right triangular and coronary ligament of the liver and ligating additional SHVs to mobilize the right lobe of the liver from the IVC.[26] After that, the patient's position and

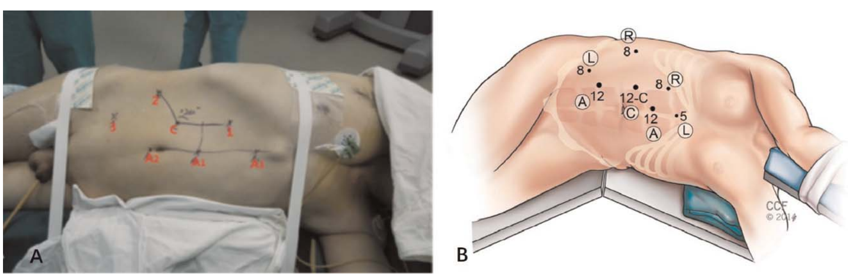

**Figure 2.** Patient's positions and port placements for robotic radical nephrectomy with inferior vena cava thrombectomy. (A) A modified left lateral decubitus position with a 70-degree bump. (B) A modified position that is with 60 degrees of table flexion at the level of the anterior superior iliac spine. Photos courtesy of Wang et al.[16] and Ramirez et al.[18]

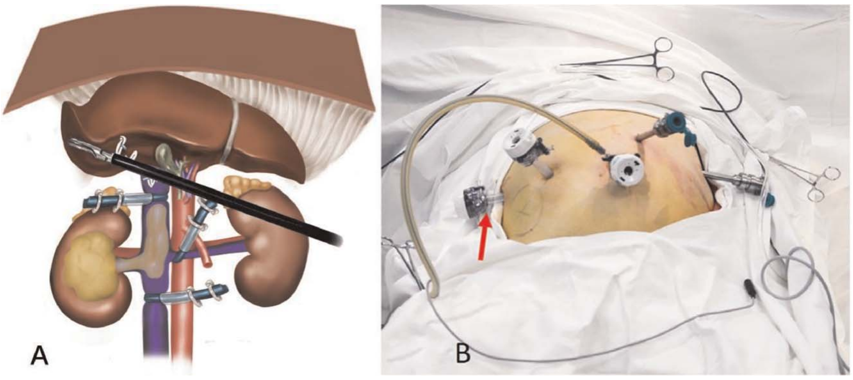


**Figure 3.** Key surgical strategies for level I–II inferior vena cava tumor thrombus ("301 Classification"). (A) Vascular control and liver retraction of level I inferior vena cava tumor thrombus. (B) Five-port method for trocar placement for liver mobilization (level II). Photos courtesy of Wang et al.[26]

port placements were converted into those described in level I IVCTT ("301 Classification").

Due to the different surgical procedures of the IVCTT above and below the FPH, the level II TT (Mayo Clinic Classification) cannot fully guide the strategy of operation; thus, it is recommended to revise the classification of the thrombus between the FPH and SPH as a "new level II."[26]

However, there are different reports on positioning strategies for level II IVCTT, especially for left-sided cases.

(1) **Pure supine position**

Aghazadeh and Goh[27] in 2018 proposed a novel supine single-dock approach (Fig. 4A) for left-sided RRN with level II IVC thrombectomy. The patient was placed in the steep Trendelenburg position. With continued bowel mobilization, a series of suspension sutures were placed with the aid of a fascial closure device. The suspension sutures anchor the incised peritoneal edges and retract in the cephalad and left lateral directions. These sutures, in concert with the steep Trendelenburg position, play a critical role in bowel retraction and retroperitoneum exposure. The supine approach is a versatile technique that yields excellent visualization and control of the entire length of the infrahepatic IVC. After the thrombectomy, the lens was transferred to a subumbilical robotic port for nephrectomy. This technique may be considered for right-sided cases as well as for IVCTT up to the hepatic veins.

(2) **Combination of lateral decubitus position and supine position**

In 2023, Zhang et al.[28] reported a novel combination of robotic and open surgeries (Fig. 4B) for the treatment of left RCC with level II IVCTT. The patient was placed in the left side of the flank position until the left kidney was almost completely detached, with the exception of the left RV. The robot was undocked, and the patient was swiftly placed in a supine position. A small supra-umbilical incision was made, and open IVC thrombectomy was performed. For large left-sided renal tumors, the extraction site must be sufficiently large to accommodate the specimen; therefore, an entirely minimally invasive technique may still require a significant extension of the extraction incision. In addition, midline open caval thrombectomy maintains excellent surgical control of the great vessels and contralateral renal hilum to improve the surgical safety compared with a completely robotic approach for left-sided tumors. However, the scope of application of this strategy is relatively limited, and its advantages are not reflected in lower or higher levels of IVCTT.

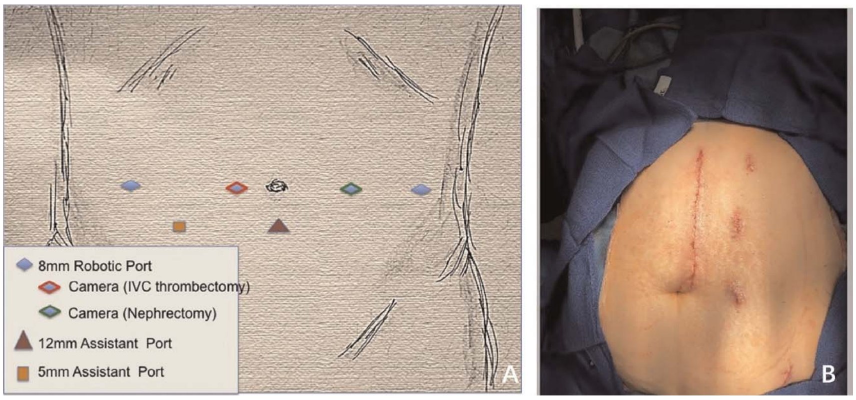


**Figure 4.** Different surgical approaches for left-sided renal cell carcinoma with level II inferior vena cava tumor thrombus ("301 Classification"). (A) The 6-port transperitoneal approach in a pure supine position (steep Trendelenburg position) for left-sided robotic radical nephrectomy with level II inferior vena cava thrombectomy. (B) Incisions for left-sided robotic radical nephrectomy with level II inferior vena cava thrombectomy, which combines robotic and open approaches. Photos courtesy of Aghazadeh and Goh[27] and Zhang et al.[28] IVC = inferior vena cava.

***Tips for exposing inferior vena cava and other important blood vessels*** Obtaining conducive exposure during robotic surgery for IVCTT is important. Bratslavsky and Cheng[29] fixed the right kidney and adrenal gland to the abdominal wall using Weck clips to expose the important anatomical structure of the renal hilum and suspended the kidney upward to obtain a stable exposure during cavotomy and reconstruction. Similarly, perirenal tissues are incompletely dissociated, and lateral renal attachments are preserved before thrombectomy,[18] which can avoid the compression of the IVC by the right kidney. Therefore, a clear surgical field of the IVC can be exposed during mobilization, cavotomy, and reconstruction, and the risk of secondary embolism may decrease.

***Inferior vena cava cavectomy*** Thrombectomy is not suitable in some cases, such as thrombosis of the IVC distal to the TT or tumor infiltration into the IVC wall, which requires partial or circumferential resection of the IVC. If the resultant defect is estimated to reduce the caval circumference by more than 50%, simple suturing of the IVC wall is not recommended.[30] The repair or reconstruction of the IVC with biomaterials is a common measure after partial or circumferential resection. Nonreconstruction is another option; however, circumferential IVC resection (cavectomy) may cause hypotension if there is no adequate preoperative assessment owing to a decrease in venous return, postoperative renal insufficiency, lower extremity edema, and abdominal wall varicosity. Our team demonstrated the feasibility of cavectomy and proposed a decision-making scheme through a multi-institutional, retrospective, case-control study.[25] For right-sided cases, Endo GIA staples the cephalic IVC below the hepatic veins with a minimal segment of the left cava to limit turbulence and potential thrombosis, and the caudal IVC is stapled below the thrombus. The left RV was circumferentially dissected and stapled. For left-sided cases, the most distinct step is dealing with the caudal IVC. The cephalic IVC and the left RV were stapled sequentially. The cross-clamping technique was used; specifically, the vessel loop was wrapped twice around the IVC between the inferior border of the left RV and the superior border of the right RV. The IVC wall was cut above the loop, and reconstruction was performed using sutures. Throughout the process, the right RV was not dissected to protect the neocollaterals (Fig. 5).

Our team also discussed the left-sided case in detail, pointing out that right RA clamping of warm renal ischemia could be avoided by suprarenal IVC control and resection. Thus, preoperative acute kidney injury can be avoided, and the right renal function can be greatly protected. However, if the TT extends to the infrarenal level, clamping of the right RA, infrarenal IVC, and its tributaries is inevitable.[31] In this case, the patient would not benefit from surgery if the collaterals of the right RV were not adequately established. Zhang et al.[32] also performed cavectomy for extensive invasion of the IVC wall and unresectable distal bland thrombus and recommended it for similar cases.

***Cephalic inferior vena cava nonclamping technique*** Zhang et al.[32] devised a prospective cohort study that compared clamping and nonclamping of the cephalad IVC during robotic level II–III thrombectomy and proved the safety and feasibility of the latter. The key step was to control the cephalic IVC by lifting the liver and increasing the pneumoperitoneum pressure to 20 mm Hg. The venous return is blocked under high pneumoperitoneal pressure; thus, IVC control is indirectly achieved. Their results showed no postoperative hypercapnia, gas embolism, or TT dislodgement in the nonclamping cohort. The advantage of this technique is that it simplifies surgical procedures. However, it is difficult to maintain a stable pneumoperitoneum pressure, and the response of each patient's vein wall to the pneumoperitoneum pressure varies, potentially increasing the risk of bleeding.

### 4.4. Level III ("301 Classification")

***The combined thoracoscopic and laparoscopic approach*** In 2015, Hui et al.[33] reported a thoracoscopy-controlled IVC approach that provided ideas for an all-port approach to resect the level III TT. They used thoracoscopic hook electrocautery and incised the pericardium longitudinally 2 cm anterior to the phrenic nerve, with $CO_2$ insufflation and intermittent apnea. Inferior exposure was improved by placing a laparoscopic finger retractor to depress the diaphragm. An articulating lighted curved dissector was used to isolate the IVC, and intraoperative real-time transesophageal ultrasonography (TEE) was used to confirm the complete cessation of caval flow upon cinching the Rummel tourniquet. Robotic thrombectomy of the right RN with the IVC was attempted; however, open conversion was necessary because of the densely adherent caval TT. The combined thoracoabdominal approach opens up an era of robotic surgery for level III IVCTT.

***Controlling the suprahepatic IVC transperitoneally*** In 2015, de Castro Abreu et al.[34] found that the suprahepatic IVC can be accessed and controlled transperitoneally in a purely robotic approach through cadaveric studies. The mobilized infradiaphragmatic suprahepatic IVC was 2–3 cm long and approximately 2.5 cm in diameter. The right and left hepatic veins were clearly visualized.

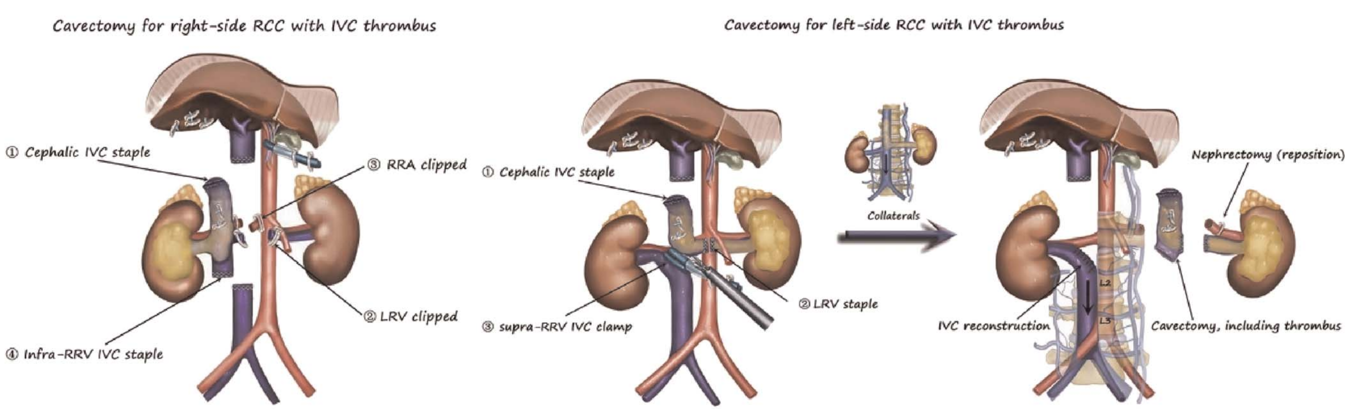


**Figure 5.** Key steps in robotic cavectomy for right-sided and left-sided RCC with IVC tumor thrombus. Photos courtesy of Shi et al.[25] IVC = inferior vena cava; LRV = left renal vein; RCC = renal cell carcinoma; RRA = right renal artery; RRV = right renal vein.

In 2018, we applied a subdiaphragmatic block approach and completed the total abdominal robotic resection of a level III TT with well-established collateral circulation.[26] The patient was placed in a 30- to 45-degree dorsally elevated lithotomy position. The right and left triangular, round, falciform, and coronary ligaments were disconnected to mobilize the right and left lobes of the liver for transperitoneal control of the suprahepatic and infradiaphragmatic IVC. After liver mobilization, the patient was shifted to a modified left thrombectomy position described in level 0 ("301 Classification") section. The caudal and left RV and cephalic IVC were sequentially dissected and clamped. After mobilizing both the right and left lobes of the liver, the suprahepatic IVC was circumferentially dissected infradiaphragmatically to penetrate the vessel loops. A vessel tourniquet was placed suprahepatically above the proximal IVC thrombus under ultrasound guidance, and the FPH was clamped simultaneously. The IVC wall was cut, the thrombus was removed, and the IVC was closed as previously described. The RRN is used as the last step.

***The nonclamping technique*** The nonclamping technique introduced by Zhang et al.[32] in 2023 was also applied to level III and low-level IV TT, which did not have to mobilize the IVC above the upper limit of the thrombus, especially for suprahepatic and infradiaphragmatic IVC control of the level III thrombus. This may help reduce the risk of TT dislodgment. As IVC control was no longer performed above the SPH, clamping the FPH was no longer necessary, thus avoiding the hepatic ischemia-reperfusion injury.

***A modified sequential vascular control strategy*** In 2020, we applied a modified sequential vascular control strategy of level III–IV TT, which mimicked the principle of the open "milking" technique, to recover liver circulation early and stop cardiopulmonary bypass (CPB).[35] Vessel tourniquets were placed below the SPH and above the proximal thrombus under intraoperative ultrasonographic guidance. Then, the caudal IVC, contralateral RV, FPH, and suprahepatic and infradiaphragmatic IVC were controlled sequentially in the "thrombectomy position." The IVC inferior to the SPH was clamped after removing the proximal portion of the thrombus from the IVC cavity, and the suprahepatic and infradiaphragmatic IVC and FPH were subsequently released. This reduced the median hepatic warm ischemia time and rate of perioperative complications. We also made an incision on the right side of the IVC wall by rotating the right lobe of the liver to the left for easy reconstruction of the SPH.

### *4.5. Level IV ("301 Classification")*

***The combined robotic and open approach*** In 2018, Palma-Zamora et al.[36] described an operation that combined robotic techniques and open surgical methods. Initially, they robotically mobilized the kidneys and IVC and subsequently performed complete nephrectomy and atrial thrombectomy through an open surgical approach. This comprehensive approach demonstrated the versatility and precision achieved by integrating robotic technology with traditional surgical techniques.

***The combined thoracoscopic and laparoscopic approach*** In 2015, Shao et al.[37] reported a combined thoracoscopic and laparoscopic approach for level IV TT. This intricate procedure involved clamping the superior vena cava, left RV, infrarenal IVC, and FPH to establish a mildly hypothermic CPB environment. Subsequently, the atrium was thoracoscopically accessed to extract the upper segment of the TT, and laparoscopy was used to remove the residual TT within the IVC. To ensure complete removal, endoscopy or TEE was performed to verify the absence of residual TT.

***The combined 3-dimensional laparoscopic and mini-thoracotomy approach*** In 2024, Crisan et al.[38] published a groundbreaking report on the management of level IV TT using a combined 3D laparoscopic and mini-thoracotomy approach. This technique was similar to that reported by Shao et al.[37] in several key respects. Notably, Crisan et al. employed a retroperitoneal laparoscopic approach that allowed rapid access to the RA while minimizing RV mobilization. This approach also facilitates better isolation of the posterior wall of the IVC, thus enhancing the precision and safety of the surgical procedure. The combined 3D laparoscopic and mini-thoracotomy approach demonstrated by Crisan et al. represents a significant advancement in the surgical management of level IV TT and offers new hope for patients facing this challenging condition.

***The step-by-step and orderly lowering strategy*** In 2020, we were the first to report a groundbreaking robotic surgical procedure for level IV TT.[35] Contrary to the findings outlined by Shao et al.,[37] our approach involved mobilizing and clamping the supradiaphragmatic IVC after addressing the intra-atrial TT. Subsequently, the abdominal segmental TT was tackled separately, adhering to the surgical technique used for level III TT.[26] The closure of vena cava and atrium were closed using continuous meticulous sutures. The FPH, left RV, caudal IVC, superior vena cava, and supradiaphragmatic IVC were released sequentially, and the CPB was ultimately terminated.

In the same year, we introduced an innovative "milking" technique, which revolutionized the surgical approach to the removal.[35] This technique involves prepositioning a vascular occlusion band beneath the liver. Under CPB, the pericardium was opened to extract the pericardial segment from the TT. Subsequently, the prepositioned occlusion band beneath the liver was tightened, and the pericardium was sutured before discontinuing the CPB and releasing the blockade of the FPH. Management of the abdominal segment of the TT followed the same surgical approach as that for level III TT.[26] This approach significantly reduced the incidence of CPB-related complications and liver function impairment.

Building on our research in 2020,[35] the Hepato-Biliary-Pancreatic Surgery Department of our center further advanced surgical techniques in 2022.[39] Specifically, when dealing with IVCTT combined with CPB and exhibiting longer lengths or adherence to the wall of the IVC, we could use a step-by-step and orderly lowering strategy, which involves gradually lowering the height of the TT in 3 distinct stages.

***Approach without cardiopulmonary bypass*** Level III–IV TT, close to the atrium, can easily cause hemodynamic instability; however, CPB can escort it. The first reported case of robotic level III–IV IVC thrombectomy by our team also explained the establishment of CPB during surgery in detail.[35] However, as long as the TT does not extend into the atrium, CPB can theoretically be avoided. Very few studies have investigated this issue in detail.

In 2020, Watson et al.[40] revolutionized surgical practice by introducing a novel approach to IVC thrombectomy that avoided the use of CPB. This innovative technique involves a robotic transperitoneal approach to secure the caudal and retrohepatic IVC, left RV, and right kidneys. Subsequently, a robotic transthoracic approach was employed to meticulously milk the TT from the right atrium. The intrapericardial caval segment was securely managed, and the right atrium was excluded. Notably, this procedure was performed without the need for CPB.

In 2023, our team further advanced surgical practice by introducing an intrapericardial control technique specifically tailored for the management of level IVa TT.[14] This innovative approach involves transperitoneal dissection of the central diaphragm tendon and pericardium to expose the pericardial vena cava. Under intraoperative ultrasound guidance, the proximal end of the TT was cranially looped. This technique offers a significant advantage, as it obviates the need for CPB and deep hypothermic circulatory arrest.

By employing this intrapericardial control technique, our team was able to achieve safer and more effective surgical outcomes in patients with level IVa TT.

In general, robotic IVC tumor thrombectomy without CPB still needs to be further explored, and its feasibility has been confirmed; however, its safety and effectiveness lack a large amount of supporting data.

## 5. Selection of preoperative adjuvant therapy

### 5.1. Neoadjuvant stereotactic ablative body radiotherapy

Chen et al.[41] revealed the considerable safety of neoadjuvant stereotactic ablative radiotherapy combined with RN and IVC thrombectomy in patients with RCC-IVCTT in a small-sample clinical trial. Unfortunately, the study used open or laparoscopic surgery; therefore, the effectiveness of neoadjuvant stereotactic radiotherapy combined with robotic surgery in the treatment of patients with RCC-IVCTT requires further study. This inspired our team to explore a multi-omics treatment model for RCC-IVCTT.

### 5.2. Renal artery embolization

Preoperative RA embolization is an important technique for the surgical treatment of RCC-IVCTT. However, researchers have held opposing views on whether it can bring benefits to surgery for decades.

A retrospective case-control study was conducted 234 patients with RCC, with or without IVCTT, by Zielinski et al.,[42] who found the apparent importance of preoperative embolization in improving the survival rate of patients. However, Subramanian et al.[43] revealed that there was no difference in intraoperative complications or length of hospitalization between embolization and nonembolization through a retrospective analysis of 225 patients with level I–IV IVCTT, and the former could even have harmful effects, such as higher perioperative mortality and increased blood transfusion in some cases. We speculate that these contradictory results may be due to bias caused by the fact that more than 87% of the samples in the first study were patients with simple RCC. Calero and Armstrong[44] recognized the value of preoperative arterial embolization when a surgeon is faced with anomalies such as variant RAs or horseshoe kidneys, because vascular configurations can be controlled more smoothly until formal ligation is completed. In 2016, our team reported that different sides require different techniques for robotic laparoscopic IVC thrombectomy and proposed that it is necessary to perform RA embolization for left RCC-IVCTT because it is difficult to expose and control the left RA when the patient is in the left LDP.[16] Subsequent researches on RCC-IVCTT by the same team also involved embolization of left-sided or large right-sided RCC[25,31] and highly recommend this procedure owing to its safety and reproducibility. Tabbara et al.[45] not only did not deny that embolization had the great advantages of intraoperative dissection of the renal tumor, decrease in the extent of the tumor, and blood loss but also expressed their views that intraoperative early ligation of the RA was technically feasible and could avoid postembolization syndrome and other side effects. Current analytical studies are mostly based on the experience with open surgery, and the lack of retrospective or prospective analyses of preoperative arterial embolization in robotic surgery leads to inconsistent conclusions.

## 6. Applications of medical consumables

### 6.1. Application of Endo GIA

Our team[16] used a novel method in a few cases of right-sided RCC, in which the right RV was ligated and disconnected from the Endo GIA before clamping the IVC, and it was applied to all cases of left-sided RCC. Therefore, the kidney and IVC thrombi were extracted separately. Endo GIA may be considered if the RV containing the TT can be disconnected with an advantage that it may reduce the chance of contact between the tumor and the abdominal organs because the IVCTT is immediately placed in the specimen bag after resection.

### 6.2. Inferior vena cava filters

In 2023, Takahara et al.[19] reported 4 cases of RRN with IVC thrombectomy; however, none of the patients used IVC filters before surgery. This is because there is no clear conclusion yet on whether the IVC filter is beneficial to the patient's operation, leading to few surgeons advocating its application. Most investigators held negative opinions on its use because the IVC filter could complicate surgical control of the proximal IVC and TT resection and even increase the risk of tumor spreading through the filter.[20,46–48] A relative review of the Cochrane Database also did not provide a firm recommendation on this issue.[49]

### 6.3. Intracaval balloon occlusion technique

In 2016, Kundavaram et al.[50] reported the control of intrahepatic or retrohepatic IVC with an intracaval occlusion balloon during robotic thrombectomy. They placed a soft-tip guidewire in the IVC through a small incision located caudal to the right RV, cephalad to the infrarenal IVC Rummel tourniquet. A Fogarty catheter was then inserted over the guidewire and passed through the TT to reach the intrahepatic location, accomplishing occlusion of the cephalic IVC. A great advantage of this technique is that the TT with less adhesion to the IVC wall can be degraded, thus reducing the difficulty of thrombectomy because the IVC incision is smaller. However, they still preplaced a vessel loop encircling the suprarenal IVC because of the risk of thrombus dislodgement. Therefore, the operative time was not effectively reduced.

Subsequently, Alahmari et al.[51] modified the technique by selecting the right internal jugular vein as the site for guidewire insertion and used a reliable stent graft balloon catheter. The entire endovascular operation was performed under fluoroscopy. This new method does not interfere with the robotic operation, thus saving surgical time.

### 6.4. Patch grafts for inferior vena cava reconstruction

Kundavaram et al.[50] reported the case of a patient with suspected malignant invasion of the IVC wall. The involved area was excised, creating an obvious caval wall defect that could not be sutured. A bovine pericardial patch was selected and circumferentially sutured to the defect. The recommended materials for IVC reconstruction include veins, biological or synthetic patches, and interposition grafting. This choice was based on the difficulty of robotic operations.

## 7. Imaging auxiliary examination equipment

### 7.1. Transesophageal ultrasonography

Currently, intraoperative laparoscopic ultrasonography is routinely used to explore the extent of TT in the IVC.[5,29] However, it occupies one of the robotic arms, even if it is temporary, and interrupts surgery. Additionally, it fails to provide ongoing real-time images; therefore, the precise extent of the TT cannot be visualized, and tumor fragments and emboli are unlikely to be detected. Moreover, once pulmonary embolism occurs, the cardiac chambers cannot be imaged. The higher the height of the TT, the more obvious the shortcomings of laparoscopic ultrasound. Therefore, alternatives are necessary, especially for proximal thrombi located in or above the retrohepatic IVC. Intraoperative TEE for open RN with IVC thrombectomy has been introduced in cardiac surgery for more than 30 years and is recommended for use in all patients with level II–IV TT.[52] Ramirez et al.[18] and Essandoh et al.[53] reported an initial series of real-time TEE monitoring procedures using a minimally invasive robotic approach. In both cases, the TT was inferior to the hepatic veins. Their investigations showed that intraoperative TEE was advantageous for determining the cranial extent and might also identify the presence of thromboembolism, which should be considered in robotic surgeries.

### 7.2. Robotic vena cavoscopy

Kundavaram et al.[50] used a flexible cystoscope that was robotically guided into the IVC through a cavotomy incision in one case to rule out vascular wall invasion or skip lesions. The examination was named robotic vena cavoscopy, which provides the operator with an all-around view without blind spots in the IVC, thereby reducing the residual TT rate.

### 7.3. Three-dimensional augmented reality guidance

Three-dimensional augmented reality is an emerging technology awaiting verification in the medical field. To explore the feasibility of 3D augmented reality guidance during robotic IVC thrombectomy, Amparore et al.[54] recruited 5 patients who met the criteria for the first application of the technique. When multiphase computed tomography images were obtained, researchers used hyperaccurate 3D reconstruction techniques to obtain highly accurate 3D virtual models of patients. The kidney boundaries, renal pedicle, and isolated IVC were used as reference points for precise manual alignment of the 3D virtual models, the transparency of which could be adjusted to visualize the TT and identify its extent. Accurate identification of the thrombus can enable selective resection of the lumbar veins and avoid clamping the contralateral RV.

## 8. Conclusions

The feasibility and reproducibility of RRN with IVC thrombectomy have been substantiated, although a global prevalence has not yet been achieved. Through the exploration of robotic surgery, numerous researchers have persistently generated novel insights and perspectives, subsequently translating them into practical applications for evaluation. This iterative process enriches collective surgical experience, thereby improving treatment outcomes. Simultaneously, they inherited, adapted, or transformed previous methodologies to streamline the procedural intricacies of robotic surgeries. All these efforts aim to mitigate perioperative mortality among patients with this condition, while facilitating a shortened learning curve for novices. The "301 Classification" reflects the objective guiding significance in robotic surgery; however, it also needs more cases to be verified and optimized for guiding surgery accurately. We are confident that the ongoing technological advancements will drive the standardization of RRN with IVC thrombectomy, potentially supplanting conventional open surgery as the preferred modality for the management of RCC with venous TT.

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## Statement of ethics

Not applicable.

## Conflict of interest statement

The authors declare that they have no conflicts of interest.

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## Author contributions

JL: Project development, data collection and literature selection, manuscript writing and editing, figure making;
ZL: Project development, data collection and literature selection, manuscript writing and editing;
QL: Data collection and literature selection, manuscript editing;
YJ: Data collection and literature selection, manuscript editing;
JL: Data collection and literature selection, manuscript editing;
HZ: Table making, literature selection, manuscript editing;
ZC: Manuscript editing, literature selection;
YD: Manuscript editing, literature selection;
XZ: Frame conception, literature selection;
XM: Frame conception, literature selection;
QH: Frame conception, literature selection;
CP: Project development, literature selection, manuscript editing;
BW: Project development, literature selection, manuscript editing.

## Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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