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Progress in Renal Tumor Surgery: The Role of 3D Surgical Planning in Partial Nephrectomy

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Abstract

Renal cell carcinoma is the most common form of kidney cancer, representing 2–3% of global cases, with the highest incidence in Western Europe. For small renal tumors, partial nephrectomy is the preferred treatment, where the tumor is surgically removed. This procedure does not affect oncological outcomes, allowing part of the kidney to remain functional. During tumor removal, the surgeon minimizes excessive bleeding and improves visibility by cutting off the arterial blood supply to the tumor. While selectively clamping the arteries feeding the tumor reduces ischemia in healthy tissue, it is crucial to have a detailed understanding of each patient's vascular structure and the blood supply to the surrounding parenchyma. Currently, the surgeon largely depends on their experience and 3D interpretation of 2D CT slices to identify the appropriate areas for clipping, which complicates preoperative planning. Indocyanine green visualization enables the inspection of tumor ischemia following clamping; however, this method only yields surface data and is only applicable intraoperatively, therefore, pre-operative planning is not possible. The goal of this thesis is to provide a planning tool that assists the surgeon in selecting the best cutting spots for partial nephrectomy surgery. To generate a 3D map of the perfusion areas for each arterial segment, a model is developed that utilizes 3D reconstructions of the renal parenchyma and arterial tree. Thus, the perfusion map enables the selection of the arterial segments supplying the cancer, and the tumor may be removed without the need for blood by clamping these vessels.

Keywords: Renal cell carcinoma, partial nephrectomy, kidney cancer, 3D reconstruction, renal perfusion mapping, arterial clamping, ischemia reduction, surgical planning tool, preoperative planning

INTRODUCTION

Renal cell carcinoma (RCC) accounts for 90% of all kidney cancers and makes up for 2–3% of all cancers. It ranks ninth among male cancers and fourteenth among female cancers. On the other hand, RCC incidence varies globally [1]. It ranks as the eleventh most common tumor in both sexes in industrialized nations, but it ranks as the twenty-first most common tumor in developing nations. There is often a 2:1 male to female predominance, with the highest occurring between the ages of 60 and 70, although the male-to-female ratio varies considerably depending on the kind of renal cell tumor and in different age groups [2]. The number of RCCs that have been clinically identified in developed nations have steadily increased during the past few decades.

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The widespread use of contemporary imaging tools is not the only explanation for the rising number of RCCs that are unintentionally discovered. Several additional elements associated with contemporary industrialized nations' lifestyles might possibly contribute to the rising incidence of RCC. Apart from inherited cases, the precise cause of RCC is still unknown. It is estimated that around one-third of RCC cases are caused by smoking [3]. In addition to smoking, which doubles the risk for RCC, the development of tumors is also linked to obesity, hypertension, and a poor diet [4]. In most European countries, the mortality rate has decreased or remained stable during the past few decades. Despite the rise in clinically identified RCC, the death rate from RCC has levelled out or even decreased in the USA and Europe [5]. Due to the extensive use of imaging techniques, smaller and lower-stage RCCs were discovered [6]. According to the data for the operation of most urological centers, the number of incidentally discovered T1a and T1b tumors is rising. When compared to cancers at higher stages, these tumors metastasis less frequently.

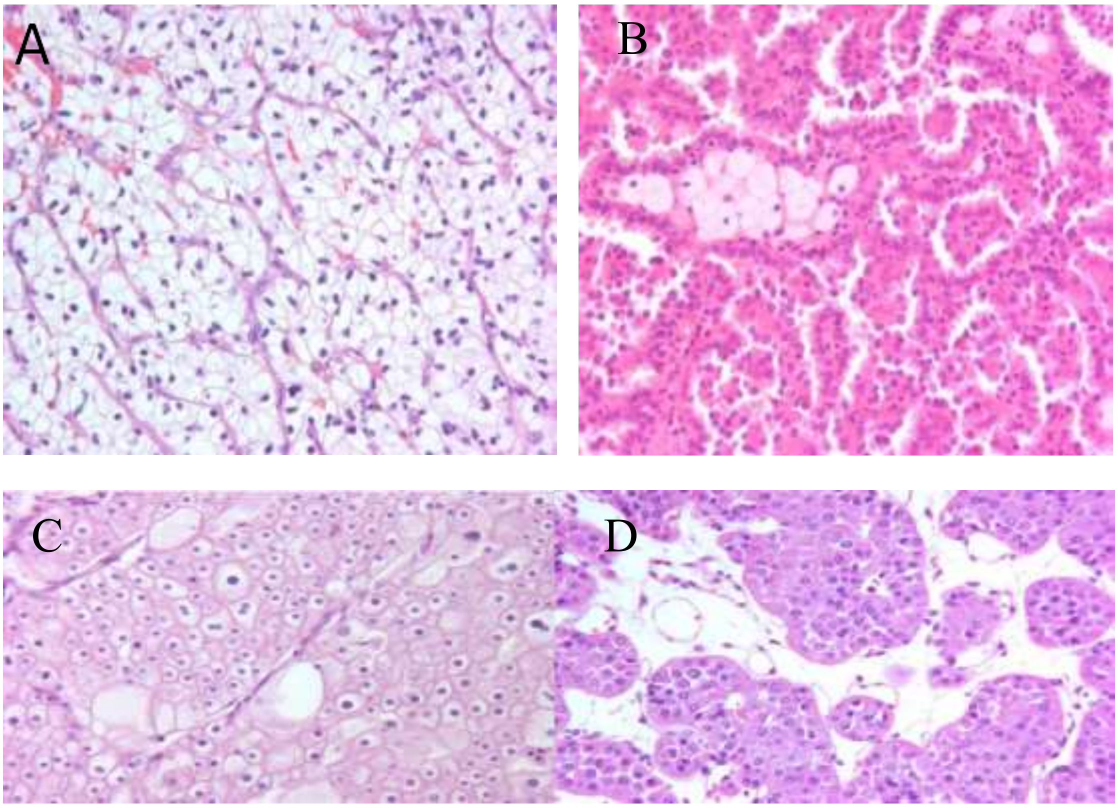

Figure 1. Histological features of four primary categories of renal cell tumors. A) RCC with pycnotic nuclei and trabecular organized, transparent cells. B) Papillary RCC with foamy cells in the papillary stalks and eosinophilic cells. C) Chromophobe RCC with double nuclei and pale cells. D) Renal oncocytoma with edematous stroma and eosinophilic cell nests. (Supplied kindly by Prof. Gyula Kovacs) (H&E, x400).

Figure 1 shows the distinctive histological features of the four primary categories of renal cell tumors. A, Typical RCC has pycnotic nuclei and trabecular organized, transparent cells with empty cytoplasm. B, Papillary renal cell carcinoma, which is made up of foamy cells in the papillary stalks and medium-sized eosinophilic cells. C, Chromophobe renal cell carcinoma, which has double nuclei organized in broad epithelial sheets and big, pale cells. D, Renal oncocytoma with edematous stroma including sizable nests of robust eosinophilic cells. (Stained with hematoxylin and eosin, x400) (Supplied kindly by Prof. Gyula Kovacs. TNM-G Classification and Staging: Predicting the disease's course).

According to Kovacs (1993) [7], 35,000 people in European nations lost their lives to renal cell carcinoma (RCC) in 2012, whereas 84,000 patients received a diagnosis. There is a direct correlation between the incidence of metastases or their postoperative development and RCC mortality. About 15–20% of the most prevalent conventional RCCs will acquire metastases within the following five years, and 20–25% of them are present with advanced illness at diagnosis. When diagnosing cancer, the tumor's stage and TNM classification are crucial factors that guide treatment and are used to predict the disease's prognosis. Patients in a cohort with a lower stage of RCC have a significantly greater cancer-specific survival rate. The tumor's size and the course of the illness are positively correlated. According to the most recent categorization, T1 tumors were either > 4 cm or < 7 cm in diameter (T1b) or ≤ 4 cm (T1a), with the former having a better

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prognosis. T2a tumors are larger than 7 cm but less than 10 cm, whereas T2b tumors are larger than 10 cm but exclusively found in the kidney. This classification could be important when deciding whether to perform a partial nephrectomy. Regional lymph node (N) positivity is another factor that affects how the disease turns out. Only one class is used in the new classification scheme, such as metastases in one or more lymph nodes. Despite contemporary targeted therapy, metastasis (M) is the final indicator of cancer malignancy and, in most cases, results in patient death. Under a microscope, the cancer cells' appearance is referred to as nuclear grading. The grade is a key prognostic indicator for RCC and reveals the potential behavior of malignancy. For kidney cancer, the most popular grading scheme is the four-grade nuclear grading system. Subsequent research, however, revealed that patients with grade 1 and grade 2 tumors have comparable survival rates and thus can be compared to as a single grade. By doing this, the three-grade system will be improved in its ability to predict the disease's fate.

METHODOLOGY

Research Context and Design

Nephrectomy Procedures

The effectiveness of safety measures is thoroughly evaluated using a mixed-methods approach that combines quantitative and qualitative research techniques.

Participants

Nephrology Department (includes supervisors, scientists, and technicians), safety officers and hospital administration, relevant parties with an interest in safety processes and protocols.

Data Gathering Tools

Questionnaires and Surveys

Structured questionnaires are intended to evaluate quantitative elements of safety, such as staff perceptions, incident reporting, and compliance rates.

Interviews

To collect qualitative information on attitudes, experiences, and recommendations for safety measures, semi-structured interviews are held with staff members.

Observational Evaluations

To assess compliance with safety procedures and the use of safety equipment, direct observations are conducted within the lab. Due to the tremendous growth of laparoscopy over the past 20 years, the 2006 European Association of Urology guidelines have recognized laparoscopic radical nephrectomy as a conventional surgical procedure.

The indication for radical nephrectomy has significantly changed in tandem with this advancement in technology. A growing proportion of tiny kidney tumors are being discovered by accident using imaging methods including computed tomography scanning and ultrasonography. Even if the contralateral kidney is functioning normally, NSS should be explored as an alternative to nephrectomy for most of these tumors because the oncologic results are comparable to those of radical nephrectomy. Nowadays, many surgeons face the challenging circumstance of being able to conduct laparoscopic NSS for tiny tumors but not for radical nephrectomy via laparoscopy for large ones. Consequently, a lot of work has gone into creating dependable and repeatable methods for laparoscopic partial nephrectomy (LPN).

To ensure precise tumor removal and minimize bleeding during renal tissue repair, partial nephrectomy is usually performed using ischemia in open surgery. Laparoscopic techniques were later shown to effectively replicate these principles of open surgery. But renal function, which is normally limited to no more than 30 minutes, depends on ischemia time. By chilling the renal parenchyma, which is simple to accomplish during open surgery, ischemia time can be significantly extended. Even the most skilled surgeons find that the ischemia period is longer with laparoscopy than with open surgery, and it is more challenging to achieve hypothermia to preserve renal function. The aforementioned issues with laparoscopic techniques have been addressed in several ways. Without ischemia, it is possible to directly exercise tiny, peripheral tumors. Radiofrequency, microwave tissue coagulator, ultrasonic scalpel, bipolar coagulation, and several other tools can be used to achieve hemostasis. Additionally, a range of tissue sealants have been employed for this function. A positive surgical margin can no longer be achieved because of the persistent searing and charring of the tissues as well as the continual bleeding, which makes it impossible to differentiate between tumor and normal parenchyma tissue. This is not the primary concern with these procedures. As such, this method is only appropriate for very specific situations.

Several technical advancements in laparoscopic partial nephrectomy have led to a significant decrease in the amount of time needed for parenchymal repair and hemostasis. The part of laparoscopic reconstructive operations that takes the longest is knotting. As a result, clips are used in place of knots. Another benefit of the big clips used for parenchyma approximation is that they prevent the suture from slicing through the parenchyma under pressure. This makes it possible to establish effective hemostasis.

MODELING AND ANALYSIS

A complicated chain of events that culminates in tissue damage and acute tubular necrosis is triggered during renal ischemia by hypoxia, which is caused by the suspension of renal blood flow, and reperfusion, which is caused by the immediate release of blood flow. Ischemia and reperfusion (IR) injury is characterized by the fact that the return of blood flow to the affected area exacerbates the initial damage induced by the ischemic insult [8]. Adenosine triphosphate (ATP) is the primary energy currency for cellular activity, and its depletion is the sentinel biochemical event in renal ischemia. The byproduct of ATP metabolism is adenosine monophosphate (AMP). The nucleosides adenosine, inosine, and hypoxanthine are produced by further metabolizing AMP after extended oxygen deprivation. The substrate reservoir for ATP production is lost because of these substances diffusing out of the cell upon reperfusion. Additionally, during the reperfusion phase, hypoxanthine acts as a crucial substrate to produce oxygen free radicals [9]. During reperfusion, xanthine oxidase contributes to the transformation of hypoxanthine into xanthine. Superoxide radicals, which are mostly derived from xanthine, are eventually converted to hydrogen peroxide and hydroxyl radicals, which cause damage to cells.

Kidney's reaction takes around half an hour [10].

RESULTS AND DISCUSSION

There were 5,682 items in all, and 14 of them satisfied the requirements for inclusion. When renal function was assessed in seven trials, the difference in means (MD) was 3.50 (95% CI: 1.16 to 5.83), favoring the absence of ischemia. There were no notable variations in intraoperative bleeding or operating time (MD, 55 mL; 95% CI, –33.16 to 144.08; and MD, 1.87; 95% CI, –20.47 to 24) (Table 1).

Table 1. Post-operative changes in serum creatinine, eGFR, T-DRF, and P-DRF of the involved kidney.

Investigated Parameters and Normal Ranges	Pre-Op (Baseline)	1-Day Post-Op	3 Days Post-Op	7 Days Post-Op	1-Month Post-Op	3 Months Post-Op	6 Months Post-Op	2 Months Post-Op	Mean of All Post-Op Results After Day 1
Serum Creatinine (62–106 µmol/l)	71 ± 14 (44–94)	86 ± 22 (43–120)	82 ± 20 (42–124)	82 ± 16 (50–112)	80 ± 16 (43–103)	79 ± 17 (47–108)	80 ± 17 (40–98)		81 (14% ↑)
eGFR (CKD-EPI) (> 90 mL/min/1.73m2)	97 ± 17 (55–122)	81 ± 21 (44–114)	87 ± 20 (55–117)	85 ± 18 (60–106)	87 ± 18 (49–114)	90 ± 21 (48–124)	87 ± 20 (54–120)		87 (10% ↓)
T-DRF of the involved kidney (%)	49 ± 4 (43–58)	Not done	Not done	Not done	42 ± 7 (24–52)	42 ± 7 (25–54)	41 ± 7 (25–52)		42 (7% ↓)
P-DRF of non-tumorous pole of involved kidney (%)	50 ± 4 (44–59)	Not done	Not done	Not done	47 ± 6 (37–57)	48 ± 5 (37–55)	46 ± 4 (35–52)	47 ± 4 (38–54)	47 (3% ↓)

Note: Post-Op: after surgery; Pre-Op: before surgery; glomerular filtration rate estimate, or eGFR; collaboration on the epidemiology of chronic kidney disease, or CKD-EPI; Both T-DRF and P-DRF stand for total and partial differential renal function, respectively.

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SERUM CREATININE-BASED ASSESSMENT OF RENAL FUNCTION

The comprehensive average results of these tests are displayed in both LPN and LRN patients and for LPN patients. Both the preoperative (time point 1) and eight postoperative checkpoints mean serum creatinine levels for the LPN and LRN groups are displayed in Figure 2. When comparing the two groups, we considered that the BMI was greater (29.7 ± 5.4 vs. 27.6 ± 4.3, p-value = 0.18), the male to female ratio was larger (73% vs. 57%), and the population in the LRN group was older (61 ± 12 years vs. 50.5 ± 11.9 years, p-value = 0.008). The LRN group's higher baseline serum creatinine level (84 umol/l) could be explained by these findings. Serum creatinine levels increased significantly right after LRN, peaking on the third post-operative day. It decreased somewhat and stayed high (123 umol/l) till the first postoperative year was over. This indicates that LRN patients' sCr levels have increased by about 46% from the baseline. Conversely, over the first three postoperative days, the serum creatinine level in the LPN group increased only little (by about 16%) from 71 umol/l to 82 umol/l, and it was constant until the conclusion of observation.

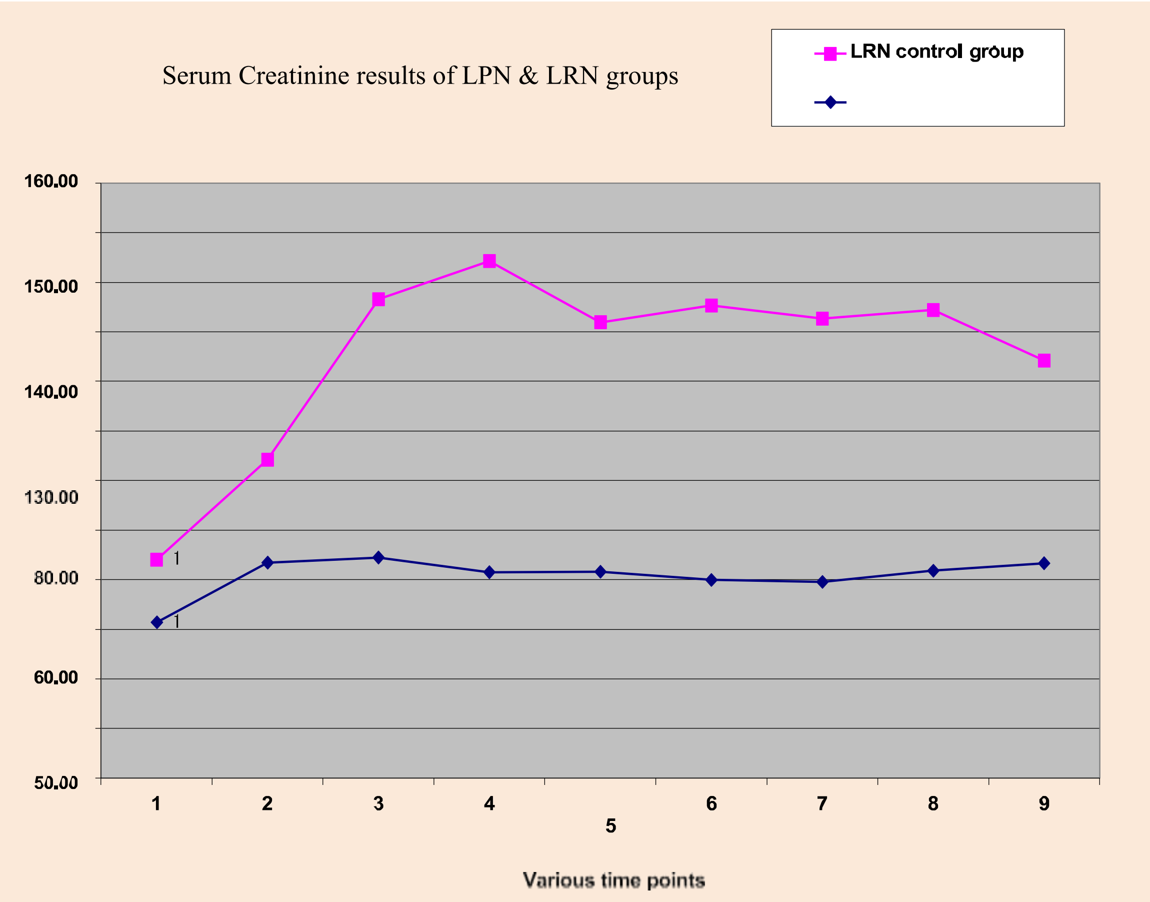

Figure 2. Changes in the parameter at various time points for the LRN control group. The data points represent the values measured at different intervals, showing a significant trend across time for both groups.

CONCLUSIONS

Our first experience with adding cold ischemia by arterial perfusion to laparoscopic partial nephrectomy demonstrates the technique's viability and safety. There has been no evidence of arterial system damage in our scant experience or in literature. Laparoscopic NSS for RCC and complex renal disease is safe and dependable – thanks to this method – which permits the replication of open surgical principles. Additionally, when difficult central tumors are surgically removed, it permits vascular healing. Along with broadening the scope of indications for more skilled laparoscopists, we believe our approach will enhance the safety of laparoscopic NSS for those with less experience.

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