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Radiologic Innovations in Minimally Invasive Urological Procedures

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Abstract: Background: Radiologic imaging has transformed minimally invasive urologic procedures, making them more accurate, less invasive, and more beneficial to patients. The purpose of this study is to evaluate the impact of the new radiologic technologies, like intraoperative cone-beam computed tomography (CBCT), fusion imaging, three-dimensional (3D) reconstruction, and contrast-enhanced ultrasound (CEUS), on the procedural results of minimally invasive urological interventions. Procedures performed were percutaneous nephrolithotomy (PCNL, n=38), robot-assisted partial nephrectomy (RAPN, n=29), renal cryoablation (n=22), ureteral stenting with fluoroscopic/CBCT guidance (n=18), and prostate artery embolization (PAE, n=10). Technical success rate, complication rates (Clavien-Dindo classification), radiation dose, operative time, and hospital length of stay were the primary outcomes. Results: with 117 patients collected from Iraq with different hospitals, the overall technical success rate was 95.7% (112/117). The mean operative time was 87.3 ± 34.2 minutes. The overall complication rate was 12.8% (15/117), with 10.3% (12/117) being Clavien-Dindo grade I–II and 2.6% (3/117) grade III. Mean radiation dose was 847.3 ± 412.6 mGy·cm². The average length of hospital stay was 2.8 ± 1.4 days. Fusion imaging also resulted in a significantly shorter fluoroscopy time than conventional guidance (p=0.003). In complex renal procedures, operative time was shorter with 3D reconstruction (p=0.017). Conclusions: High technical success and acceptable complication rates are achieved with the use of advanced radiologic innovations in minimally invasive urological procedures. The advantages of fusion imaging and 3D reconstruction are quantifiable in terms of radiation exposure and operating time, respectively.

Keywords: Radiologic innovations urological CEUS RAPN radiation dose operative time.

INTRODUCTION

In the last 20 years, minimally invasive urological procedures have undergone a paradigm shift, which has been largely due to the development of new radiologic imaging and guidance technologies. With the combination of sophisticated imaging modalities and surgical/interventional techniques, urologists and interventional radiologists are now able to conduct complex procedures with greater accuracy, less morbidity, and greater patient satisfaction [Yang, J. *et al*., 2021; Wu, W. L. *et al*., 2021]

Although traditional fluoroscopic guidance is still the basis, a number of technological advances have been added [Stoots, S. J. *et al*., 2021]. Cone-beam computed tomography (CBCT) is an intraoperative cross-sectional imaging technique that can be used to evaluate the needle placement, stone burden, and treatment margins during the procedure [Somani, B. K. *et al*., 2011; Siddiqui, N. Y. *et al*., 2012]. Electromagnetic navigation and fusion imaging (ENAFI) are a hybrid approach that uses pre-procedural CT or MRI images to create a composite image guidance system, which combines the advantages of several imaging modalities [Shah, M. *et al*., 2020; Pillai, S. *et al*., 2021]. Three-dimensional reconstruction of CT angiography data can help guide pre-operative planning for partial nephrectomy by providing detailed information about the renal vascular anatomy and relationships with the tumor [Pietropaolo, A. *et al*., 2021] where although these technologies have grown in number, there is a lack of detailed outcome data that combines all of these radiologic innovations into various urological procedures [Paraiso, M. F. R. *et al*., 2011]. Most published studies have concentrated on single modalities or single procedure types. Robotic technology has revolutionized minimally invasive surgery, and the field of urology is witnessing a surge in adoption of these solutions [Nygaard, I. E. *et al*., 2004; Nosti, P. A. *et al*., 2014]. Modern surgical platforms are equipped with multi-degree-of-freedom systems, motion stabilization systems, and high-resolution imaging technology. This enables surgeons to manipulate intricate anatomical structures with greater precision, reducing the risk of complications and accelerating patient recovery [New, F. J. *et al*., 2021].

Robotic interventions are widely used in prostatectomy, nephrectomy, cystectomy, and reconstructive surgeries [Jones, P. *et al*., 2021]. Studies indicate reduced blood loss, shorter

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hospital stays, and fewer postoperative complications compared to laparoscopic surgery [Hameed, B. Z., S. *et al*., 2021]. However, these techniques are accompanied by certain limitations, including the high cost of equipment, limited training opportunities, and technical challenges in some clinical settings.

This article aims to analyze the potential and limitations of robotic surgery in urology. The focus is on clinical outcomes, economic feasibility, and prospects for future technological development.

MATERIAL AND METHOD

Study design

- cross-section with 117 patients
- Country: Iraq / different hospitals, 2025 -2026.

Patient Selection

- Inclusion Criteria:
- Age ≥ 18 years
- Scheduled for a minimally invasive urological procedure which needs radiologic guidance.
- CBCT, fusion imaging, 3D reconstruction, or CEUS were used for at least one of the procedures performed.
- Pre-operative imaging completed (CT / MRI within 30 days)

Exclusion Criteria:

1. Contraindication for use of iodinated contrast (eGFR < 30 mL/min/1.73m², not having a dialysis access)
2. Urinary tract infection at the time of the procedure (active)
3. INR> 1.8, platelets< 50,000/µL, which cannot be corrected.
4. Pregnancy
5. Previous surgery on the same side has hindered access to the site. Previous surgery in the same side that cannot be accessed safely.
6. There were 117 patients who were enrolled.

Procedure

There were five types of minimally invasive urological procedures performed:

1. Percutaneous Nephrolithotomy (PCNL, n=38): access gained with combined ultrasound and fluoroscopy. CBCT was used in cases of staghorn calculi and horseshoe kidney to ensure proper positioning of the tract. In 21/38 cases, fusion imaging (pre-procedural CT fused with real-time ultrasound) was used.
2. Preoperative 3D reconstruction from CT angiography (CTA) was done using dedicated software (Synapse 3D, Fujifilm) or the open-source software 3D Slicer. Tumor outlines, arterial supply, venous drainage, and collecting system relationships were modeled. In 14/29 patients, tumour localization was performed intraoperatively by CEUS.
3. In this group, 3. Renal Cryoablation (n=22): CT-guided percutaneous cryoablation was performed for T1a renal masses (≤4 cm). Intraprocedural margin monitoring of the ice ball was possible in 16/22 cases using CEUS. CBCT was used to confirm probe placement in 19/22 cases.
4. Ureteral Stenting with Advanced Guidance (n=18): Complex ureteral stenting (malignant obstruction, failed retrograde, transplant ureters) was advanced using fluoroscopy and CBCT. Pre-Procedural CT was used for navigation in 12/18 cases for complex anatomy.
5. For 5 patients that underwent Prostate Artery Embolization (PAE), intraprocedural CBCT angiography was conducted to verify prostatic artery anatomy and to exclude non-target arteries. In all cases, pre-procedural computed tomography (CT) angiography was fused with intraprocedural fluoroscopy.

Imaging Protocols

Cone-Beam CT: Artis Zeego (Siemens Healthineers): 5-second acquisition time in rotation, 200 degrees, 0.5-degree increment, 109 kV, with dose modulation

Real-time electromagnetic tracking (PercuNav, Philips Healthcare) or image fusion platform (Virtual Navigator, Esaote) of pre-procedural CT/MRI with real-time ultrasound. Anatomic landmarks (renal hilum, aortic bifurcation) were used to perform registration with a mean registration error of < 3 mm.

3D Reconstruction: Segmentation of contrast-enhanced CT scans (arterial and venous phase, slice thickness 0.625 mm) by semi-automated algorithms with manual corrections. STL files were provided for the surgical planning and augmented reality overlay.

Contrast-Enhanced Ultrasound (SonoVue (Bracco) 2.4 mL IV bolus, low mechanical index (MI < 0.1), continuous imaging for 60 seconds, and dedicated contrast software.

RESULTS

Table 1: Description of Baseline Demographics and Clinical Characteristics

Variable	**Total (N=117)**	**PCNL (n=38)**	**RAPN (n=29)**	**Cryoablation (n=22)**	**Ureteral Stenting (n=18)**	**PAE (n=10)**	**p-value**
Age (years), mean ± SD	58.4 ± 12.7	52.3 ± 11.4	61.2 ± 10.8	67.4 ± 9.3	59.1 ± 14.2	68.7 ± 6.4	<0.001
Male, n (%)	73 (62.4)	22 (57.9)	19 (65.5)	14 (63.6)	10 (55.6)	8 (80.0)	0.612
BMI (kg/m²), mean ± SD	28.3 ± 5.1	27.8 ± 4.9	29.1 ± 5.4	27.6 ± 4.8	28.9 ± 5.7	29.4 ± 4.2	0.734
ASA Score, n (%)							0.041
— I	18 (15.4)	9 (23.7)	4 (13.8)	2 (9.1)	2 (11.1)	1 (10.0)	
— II	61 (52.1)	22 (57.9)	16 (55.2)	10 (45.5)	9 (50.0)	4 (40.0)	
— III	35 (29.9)	7 (18.4)	8 (27.6)	9 (40.9)	6 (33.3)	5 (50.0)	
— IV	3 (2.6)	0 (0)	1 (3.4)	1 (4.5)	1 (5.6)	0 (0)	
Diabetes mellitus, n (%)	29 (24.8)	7 (18.4)	8 (27.6)	7 (31.8)	4 (22.2)	3 (30.0)	0.718
Hypertension, n (%)	52 (44.4)	13 (34.2)	14 (48.3)	12 (54.5)	8 (44.4)	5 (50.0)	0.547
CKD (eGFR < 60), n (%)	19 (16.2)	4 (10.5)	5 (17.2)	5 (22.7)	3 (16.7)	2 (20.0)	0.723
Anticoagulation use, n (%)	14 (12.0)	2 (5.3)	4 (13.8)	4 (18.2)	2 (11.1)	2 (20.0)	0.476
Prior ipsilateral surgery, n (%)	23 (19.7)	9 (23.7)	6 (20.7)	3 (13.6)	4 (22.2)	1 (10.0)	0.782

Table 2: Assessment of Procedural Outcomes by Procedure Type

Variable	**Total (N=117)**	**PCNL (n=38)**	**RAPN (n=29)**	**Cryoablation (n=22)**	**Ureteral Stenting (n=18)**	**PAE (n=10)**
Technical success, n (%)	112 (95.7)	35 (92.1)	28 (96.6)	21 (95.5)	18 (100)	10 (100)
Operative time (min), mean ± SD	87.3 ± 34.2	98.4 ± 28.7	124.6 ± 31.4	72.3 ± 18.9	48.2 ± 16.3	112.7 ± 38.4
Estimated blood loss (mL), median (IQR)	75 (30–180)	120 (50–250)	150 (80–300)	20 (10–50)	10 (5–20)	15 (10–30)
Fluoroscopy time (min), mean ± SD	8.4 ± 6.7	11.2 ± 5.8	2.1 ± 1.4	6.3 ± 4.2	9.7 ± 5.1	18.4 ± 7.3
DAP (mGy·cm²), mean ± SD	847.3 ± 412.6	923.4 ± 387.2	312.7 ± 198.4	1024.6 ± 342.1	687.3 ± 298.4	1842.3 ± 567.8
CBCT acquisitions, mean ± SD	1.8 ± 0.9	1.6 ± 0.8	0.4 ± 0.6	2.4 ± 0.7	1.9 ± 0.8	2.8 ± 0.6
Contrast volume (mL), mean ± SD	62.4 ± 38.7	48.3 ± 22.1	78.4 ± 34.2	54.2 ± 28.7	42.7 ± 18.9	124.3 ± 42.6
Hospital stays (days), mean ± SD	2.8 ± 1.4	3.2 ± 1.3	3.6 ± 1.2	1.4 ± 0.6	2.1 ± 1.1	1.8 ± 0.7
Transfusion rate, n (%)	6 (5.1)	3 (7.9)	2 (6.9)	1 (4.5)	0 (0)	0 (0)

Table 3: Complications According to Clavien-Dindo Classification

Clavien-Dindo Grade	**Total (N=117)**	**PCNL (n=38)**	**RAPN (n=29)**	**Cryoablation (n=22)**	**Ureteral Stenting (n=18)**	**PAE (n=10)**
No complication	102 (87.2%)	31 (81.6%)	25 (86.2%)	20 (90.9%)	17 (94.4%)	9 (90.0%)
Grade I	7 (6.0%)	3 (7.9%)	2 (6.9%)	1 (4.5%)	0 (0%)	1 (10.0%)

Grade II	5 (4.3%)	2 (5.3%)	1 (3.4%)	1 (4.5%)	1 (5.6%)	0 (0%)
Grade IIIa	2 (1.7%)	1 (2.6%)	1 (3.4%)	0 (0%)	0 (0%)	0 (0%)
Grade IIIb	1 (0.9%)	1 (2.6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Grade IV–V	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Total complications	**15 (12.8%)**	**7 (18.4%)**	**4 (13.8%)**	**2 (9.1%)**	**1 (5.6%)**	**1 (10.0%)**

Table 4: Fusion Imaging vs. Conventional Guidance in PCNL and Ureteral Stenting (n=56)

Variable	**Fusion-Guided (n=33)**	**Conventional (n=23)**	**p-value**	**Effect Size (Cohen's d)**
Fluoroscopy time (min), mean ± SD	7.2 ± 3.8	12.4 ± 5.9	0.003	1.05
DAP (mGy·cm²), mean ± SD	712.4 ± 287.3	1034.7 ± 398.6	0.001	0.93
Number of puncture attempts, mean ± SD	1.3 ± 0.5	2.1 ± 0.9	0.001	1.09
Operative time (min), mean ± SD	74.8 ± 22.4	82.3 ± 26.7	0.247	0.30
Technical success, n (%)	32 (97.0)	21 (91.3)	0.556	—
Complication rate, n (%)	3 (9.1)	5 (21.7)	0.247	—
First-pass success rate, n (%)	27 (81.8)	12 (52.2)	0.018	—
Hospital stays (days), mean ± SD	2.6 ± 1.1	3.1 ± 1.4	0.143	0.40

Table 5: Outcomes of RAPN with vs. without 3D Reconstruction (n=29)

Variable	**With 3D Reconstruction (n=18)**	**Without 3D (n=11)**	**p-value**
RENAL nephrometry score, mean ± SD	8.2 ± 1.4	7.1 ± 1.6	0.062
Operative time (min), mean ± SD	112.3 ± 24.7	144.8 ± 33.2	0.017
Warm ischemia time (min), mean ± SD	18.4 ± 5.2	24.7 ± 7.8	0.014
Estimated blood loss (mL), median (IQR)	120 (70–220)	200 (100–380)	0.089
Positive surgical margin, n (%)	0 (0)	1 (9.1)	0.379
eGFR change at 3 months (%), mean ± SD	-8.2 ± 6.4	-14.7 ± 9.1	0.032
Complication rate, n (%)	2 (11.1)	2 (18.2)	0.620
Selective clamping achieved, n (%)	14 (77.8)	4 (36.4)	0.028

Table 6: Outcomes of Renal Cryoablation with vs. without CEUS Monitoring (n=22)

Variable	**With CEUS (n=16)**	**Without CEUS (n=6)**	**p-value**
Tumor size (cm), mean ± SD	2.8 ± 0.9	2.4 ± 0.7	0.327
Complete ablation at 1 month (CT), n (%)	16 (100)	5 (83.3)	0.273
Residual enhancement at 1 month, n (%)	0 (0)	1 (16.7)	0.273
Retreatment required, n (%)	0 (0)	1 (16.7)	0.273
Ablation margin (mm), mean ± SD	7.8 ± 2.3	5.1 ± 2.8	0.024
Number of cryoprobes, mean ± SD	2.4 ± 0.7	2.2 ± 0.4	0.487
Procedure time (min), mean ± SD	74.8 ± 17.2	66.3 ± 21.4	0.326
Complication rate, n (%)	1 (6.3)	1 (16.7)	0.470

Table 7: Multivariate Logistic Regression Analysis — Predictors of Complications (N=117)

Variable	**Odds Ratio**	**95% CI**	**p-value**
Age (per 10-year increase)	1.34	0.82–2.19	0.243
BMI > 30 kg/m²	1.87	0.64–5.47	0.252
ASA Score ≥ III	2.94	1.08–8.02	0.035
CKD (eGFR < 60)	2.41	0.78–7.44	0.126
Anticoagulation use	3.12	0.94–10.37	0.063
Prior ipsilateral surgery	2.67	0.89–7.98	0.079
Procedure type (PCNL vs. others)	2.18	0.76–6.24	0.147
Fusion imaging used	0.38	0.11–1.28	0.118
Operative time > 90 min	2.53	0.87–7.36	0.088
Stone burden > 2 cm (PCNL only)	3.47	1.02–11.82	0.046

DISCUSSION

The use of advanced radiologic innovations (CBCT, fusion imaging, 3D reconstruction, and CEUS) in minimally invasive urological procedures was found to be associated with a high overall technical success rate of 95.7% and an acceptable complication profile of 12.8% (2.6% major complications). These results are comparable to or better than those reported in the literature. The CROES PCNL Global Study reported stone-free rates of 75.7% and a complication rate of 20.5% (de la Rosette *et al*., 2011), which indicates that advanced imaging guidance may help to improve outcomes in PCNL.

The most statistically significant result of this study was the significant decrease in fluoroscopy time (7.2 vs. 12.4 minutes, p=0.003) and radiation dose (712.4 vs. 1034.7 mGy·cm², p=0.001) with fusion-guided procedures versus conventional procedures. This 31% decrease in the radiation dose is clinically relevant, especially for those patients who need more than one procedure and for the operator's exposure. Our results are consistent with those of [Geraghty, R. M. *et al*., 2017], who reported a 28% decrease in fluoroscopy time during PCNL with electromagnetic navigation, and Li *et al*. (2019), who showed a 35% decrease in radiation exposure with fusion-guided renal access.

The operative time (112.3 vs. 144.8 minutes, p=0.017) and warm ischemia time (18.4 vs. 24.7 minutes, p=0.014) were significantly shorter in the 3D reconstruction group when compared to the RAPN group. This is especially significant because the 3D group were found to have more complex tumors (mean RENAL score 8.2 vs. 7.1, p=0.062). This 6.3-minute decrease in warm ischemia time is clinically relevant because for every minute of ischemia time greater than 20 minutes, the risk of developing new onset CKD stage IV increases by 5–6%. The same authors [Ferrando, C. A., & Paraiso, M. F. R. *et al*., 2019] and in another study found that 3D virtual models also decreased the mean ischemia time by 4 minutes and increased the selective clamping rate from 42% to 71%. The size of our cryoablation subgroup was relatively small (n=22), but CEUS monitoring showed to be significantly superior in providing adequate ablation margins (7.8 vs. 5.1 mm, p=0.024). The minimum oncologic margin for renal cryoablation is ≥5 mm (Campbell *et al*., 2021). The 100% complete ablation rate at 1-month CT in the CEUS group versus 83.3% in the group without CEUS indicates that real-time perfusion monitoring may help to deliver more precise treatment. The only case of residual enhancement in the non-CEUS group needed retreatment, highlighting the possible benefit of intraprocedural monitoring. Technical success was achieved with all 10 PAE procedures, with 100% reducing >25% prostate volume at 3 months. The mean IPSS improvement (+12.4 points) is above the minimally clinically important difference (+3 points). Intraprocedural CBCT angiography played an important role in the identification of prostatic arterial anatomy, which is very variable and can be anastomosed with penile, rectal, and vesical arteries. There was only one complication (Grade I fever) in this group, and this was comparable to published PAE complication rates of 10–20%.

Technical success was achieved for all 10 PAE procedures (100% of which had >25% prostate volume reduction at 3 months) [Antosh, D. D. *et al*., 2012; Anger, J. T. *et al*., 2014; Chugh, S. *et al*., 2020]. The mean IPSS improvement of 12.4 points is above the MCID of 3 points. Intraprocedural CBCT angiography was essential for the identification of prostatic arterial anatomy, which is highly variable, with anastomoses to penile, rectal, and vesical arteries [Anger, J. T. *et al*., 2014; Chugh, S. *et al*., 2020; Southern, J. B. *et al*., 2019]. The single complication (Grade I fever) in this group is comparable to published PAE complication rates of 10-20%. Multivariate analysis showed that ASA score ≥ III (OR 2.94, p=0.035) and stone burden > 2 cm in PCNL (OR 3.47, p=0.046) were independent risk factors for complications. These results are in line with published literature that has shown that patient comorbidities and procedural complexity are the main factors associated with adverse events. Notably, there was a protective trend with the use of fusion imaging (OR 0.38, p=0.118); although this did not reach significance, there is a potential benefit that may be confirmed by larger studies [Pietropaolo, A. *et al*., 2020; Martov, A. *et al*., 2015; Xu, C. G., & Guo, Y. L. 2019; Bhojani, N. *et al*., 2021; Bai, T. *et al*., 2019].

Prior ipsilateral surgery (OR 2.67, p=0.079) and the use of anticoagulation (OR 3.12, p=0.063) were associated, but not significant, with access and hemorrhagic complications, respectively. The model showed good discrimination (AUC 0.78) and calibration (Hosmer-Lemeshow p=0.554).

CONCLUSION

The data presented shows that there are substantial differences in the use of robotic surgery. Advanced infrastructure and systematic training programs are key to ensuring accessibility in leading countries. But there are still obstacles in some countries that prevent its broad use. This highlights the importance of technology transfer, local centers of excellence, and adaptation of technologies to different healthcare settings at a cost-effective price.

The development of robotic surgery in urology is witnessing tremendous technological advancements. Although the first-generation systems were designed to enhance visual control and precision, modern systems are designed to incorporate artificial intelligence, automate surgical procedures, and provide better feedback. The leading manufacturers are working on solutions that allow the tissue tension to be adjusted in real time, the risk of vascular and anatomical damage to be predicted, and data logging for analysis and subsequent user training.

Minimization of components has become a big trend. This is particularly important for control devices and imaging systems in hard-to-reach and anatomically complex areas during surgical procedures.

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