Journal of Endourology

DOI: 10.1089/end.2017.0174

Title: Adoption of robotic assisted partial nephrectomies: A population-based analysis of U.S. surgeons from 2004-2013

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Conflicts of Interest and Source Funding: None declared

Keywords: Partial nephrectomy, robotics, law of diffusion, adoption

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This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof.

1. Introduction

The advent of minimally invasive and robotic techniques has resulted in the rapid adoption of this novel technology, with the field of urology at the forefront. Since the first Robotic-Assisted Laparoscopic Radical Prostatectomy (RALP) was performed in 2000 using the *da Vinci Surgical System* (Intuitive Surgical, Inc., Sunnyvale, CA, USA), surgeons have rapidly incorporated robotic technology for the use of radical prostatectomies for prostatic carcinoma. Prior to 2005, only a minority of surgeons--fewer than 2.5%--performing radical prostatectomies utilized robotic assistance. However, robotic assistance has become the predominant approach for radical prostatectomies, increasing from 22% to 85% between the years 2002 to 2013, representing a nearly five-fold increase in utilization.[1]

Studies have shown that minimally invasive approaches in general, with or without robotic assistance, reported lower rates of blood loss, transfusion rates, and catheterization time. [2,3] However, the benefits of robotic over laparoscopic approaches for partial nephrectomies requires additional study, as there is an absence of head-to-head randomized controlled trials comparing RAPN and LPN. Early meta-analyses reported comparable outcomes between LPN and RAPN, including operative times, estimated blood loss, conversion rates, complication rates, and number of positive margins, though a robotic approach was associated with decreased warm ischemia times.[4,5] Other studies have also found RAPN to be associated with higher costs, though these were partially offset by a shorter length of stay.[6–9] Only recently, long-term outcomes of RAPN have become available, with studies showing comparable 3-year and 5-year recurrence-free survival rates between RAPN and LPN.[10,11]

Though early meta-analyses did not indicate a clear advantage to a robotic approach, later studies have shown RAPN to have a significant advantage over LPN. A recent meta-analysis by Leow et al. including 4,919 patients concluded that RAPN had lower rates of any or major complication scores, fewer positive margins, and shorter warm ischemia time.[12] A retrospective multi-institutional study by Zargar et al. comparing 1,185 robotic partial nephrectomies and 646 laparoscopic partial nephrectomies with “Trifecta” as the primary outcome (a composite outcome of negative margin, no complications, and a warm ischemia time < 25 minutes) found that a robotic approach achieved much higher trifecta rates compared to a laparoscopic approach (70% vs. 33%).[13] Another retrospective study by Ghani et al. including 38,064 partial nephrectomies from the National Inpatient Sample showed lower rates of intraoperative complications as well as higher hospital charges with robotic procedures.[14] Additional evidence suggests that patients undergoing RAPN are also less likely to be readmitted, though these also patients accumulated higher excess hospital charges.[15] In summary, though earlier evidence suggested equivocal results between RAPN and LPN, more recent studies have shown advantages to a robotic approach with partial nephrectomies, though these have been associated with higher costs to the health care system.

Additionally, adoption of RAPN has been rapid, with Ghani et al. reporting an annual increase in utilization of 45.4% compared to 7.9% and 6.1% for open and laparoscopic approaches in 2010.[14] Additionally, other institutional studies have shown that robotic assistance is rapidly becoming the predominant modality for partial nephrectomy.[15,16] Robotic assistance has become the predominant approach for radical prostatectomies, increasing from 22% to 85% between the years 2002 to 2013, representing a nearly five-fold increase in utilization.[1]

Given the swift incorporation of robotic assistance in urological practice, the main factors driving a clinician's decision to utilize robotic technology becomes an important practice-based question. Although our group has previously described the relevant factors for robotic adoption into radical prostatectomies,[17] the same analysis has not yet been done for Robotic-Assisted Partial Nephrectomies (RAPN), which are commonly performed for low-stage renal tumors. The purpose of this study is to describe the adoption pattern of robotic-assisted technology for partial nephrectomies and determine the relevant hospital and surgeon-specific factors affecting a surgeon's decision to utilize robotic assistance in performing a partial nephrectomy.

2. Methods

2.1 *Study Cohort*

This is a retrospective population-based study utilizing the Premier Hospital Database (Premier Inc., Charlotte, NC, USA), a nationally representative sample capturing 20% of all inpatient admissions. All hospital admissions data were de-identified prior to analysis and institutional review board exemption was granted from our institution. We identified all men receiving a partial nephrectomy using the International Classification of Diseases, Ninth Revision (ICD-9) code (*55.4, partial nephrectomy*). The study period extended from January 1, 2004 to December 31, 2013, in order to capture the primary period of robotic diffusion in the United States. The Premier Database contains comprehensive billing data for each patient, which was utilized to identify and separate out open, laparoscopic, and robotic procedures. This was done using a detailed review of the charge description master (CDM) for each patient, which details specific operating room supplies unique to robotic procedures. The CDM was also used to generate a robotic variable indicating which hospitals had an available da Vinci robot; observations were dropped from the analysis if we were unable to confirm the presence or absence of a robot using the CDM.

2.2 *Physician Volume and Adoption*

The Premier database also contains unique physician identifiers, allowing us to quantify each individual attending's annual surgical volume. This data was used to categorize surgeons into lowand high-volume surgeons based on clinical reasoning. The surgical volume categories were defined according to clinical experience; "low-volume" was defined as five or fewer partial nephrectomies annually and "high-volume" was defined as greater than fivecases per year. Our outcome variable was defined as the percentage of nephrectomies that were performed robotically each year for an individual surgeon.

2.3 *Patient and Hospital Characteristics*

We evaluated baseline patient characteristics that had the potential to influence the decision to utilize robotic surgery including age (<40, 41-50, 51-60, 61-70, >70), race (White, Black, Hispanic, Other), and insurance status (Medicare, Medicaid, Private Insurance, Other). To account for baseline health status, we calculated the Charlson Comorbidity Score (CCS), a measure of a patient's illness that is predictive of ten-year mortality rates. [18] We also examined relevant hospital characteristics including number of beds (<200, 200-399, ≥400), type (teaching or non-teaching), location (urban or rural), and region (Midwest, Northeast, South, West).

2.4 *Statistical Analysis*

A descriptive summary of patient and hospital characteristics was performed for patients undergoing robotic-assisted and non-robotic assisted nephrectomies (either open or laparoscopic procedures). Chi-squared tests using the Rao-Scott correction factor were performed on baseline patient characteristics in order to examine the correlation between explanatory variables and type of surgical approach (open, laparoscopic, robotic) for nephrectomies. We limited the analysis to surgeons performing partial nephrectomies at hospitals with an available robot and examined yearly trends in adoption rates of robotic nephrectomies over time, defined as the percentage of partial nephrectomies performed robotically, averaged across all surgeons.

We then constructed multivariate linear regression models to determine relevant factors for robotic assisted partial nephrectomy adoption, such as academic vs community settings, urban vs. rural populations, hospital size, volume of surgical cases, and region. These multivariate linear regression models were stratified by different time periods according to the Law of Diffusion of Innovation, including the innovator, early adopter, and early majority phases. By definition, the innovator, early adopter, and early majority time periods correspond to when 2.5%, 16%, and 50% of the population have adopted a novel technology, respectively. [8,15,16] Only surgeons practicing at hospitals with available da Vinci surgical systems were included in the regression analysis.

For these analyses, we applied survey weighting to generate a nationally representative sample. All statistical tests were two-sided and an α level of <0.05 was considered statistically significant. All analyses were performed using Stata 14 Statistical Software (College Station, TX).

3. Results

Within this study, a total of 16,592 partial nephrectomies were performed on men between the years of 2004-2013. Of these observations, the presence or absence of a robot at the admitting hospital could be determined for 14,890 observations, all of which were included in the study. The baseline characteristics of these patients are described in Table 1, which showed no significant differences between patients who did and did not receive robotic assistance.

3.1 *Diffusion of robotic-assisted nephrectomies*

There was a progressive increase in the adoption of robotic assistance for partial nephrectomies in the United States from 2004-2013, similar to earlier findings of rapid diffusion of robotic technology for radical prostatectomies.[1] Throughout this entire period, from 2004-2013, 32% of partial nephrectomy cases were performed robotically. According to the Law of Diffusion, the innovator, early adopter, and early majority phases for the technological adoption of RAPN occurred from 2004-2005, 2006-2008, and 2009-2013, respectively (Figure 1). The percentage of partial nephrectomies performed robotically grew steadily from 1.3% to 2.3% during the innovator phase, then quickly quadrupled during the early adopter phase from 3.7% to 12.1%. By the end of the early majority phase in 2013, the percentage of PNs performed withrobotic technology had increased to 64.1%.

3.2 *Relevant factors for robotic assistance utilization for partial nephrectomies*

For our multivariate linear regression analysis, we examined the percentage of partial nephrectomies performed robotically within the innovator, early adopter, and early majority phases, according to the Law of Diffusion of Innovation (Table 2). During the innovator phase, we found no variables to be predictive of robotic assistance for PNs. During the early adopter phase, which contains the steepest period of growth in technological adoption, both surgical volume and year of surgery were significant predictors of robotic adoption. High-volume surgeons (>5 PN/year) were 7.0% more likely to perform their partial nephrectomy robotically compared to their low-volume colleagues (<5 PN/year) ($p=0.049$) and the utilization of robotic assistance for partial nephrectomies increased by 4.6% with each passing year ($p<0.001$). These factors were re-enforced during the early majority phase, during which a majority of surgeons utilized robotic assistance. Surgical volume and year of surgery continued to be strong predictive variables, with high-volume surgeons performing 23.2 % more PNs robotically ($p<0.001$) than their low-volume colleagues and an increase in robotic assistance by 8.6% ($p<0.001$) with each progressive year from 2009-2013. Interestingly, hospitals in the Northeast performed 16.7% fewer robotic partial nephrectomies compared to their Midwest counterparts.

4. Discussion

This study examines the distinct similarities and differences between the adoption pattern of robot-assisted partial nephrectomies compared to robot-assisted laparoscopic prostatectomy, which has been previously described in the literature.[17] Additionally, we examined national trends in robotic partial nephrectomy from 2004-2013. While Ghani et al found that a majority of partial nephrectomies still utilized an open approach in 2010, we found that by 2013, a clear majority of PNs (64.1%) were performed robotically by 2013 (Figure 1).[14] According to our findings, trends in technological diffusion occurred a year later for RAPN compared to RALP, likely due to several factors. [19,20] We theorize that unlike RALP adoption, which was initially driven by marketing and patient demand, RAPN adoption was most likely driven by RALP surgeons now familiar with the robotic platform, utilizing it for the more complex partial nephrectomy. Though our study is currently limited to partial nephrectomies, this is a potential topic for future research. [21,22] The reasons for doing so reflect the advantages of using robotics for RAPN, including magnification and greatly improved dexterity allowing for accurate intra-corporeal suturing, allowing surgeons to overcome the technical challenges inherent with laparoscopic partial nephrectomies. [23,24] Unlike RALP, where the initial adoption occurred in academia, for RAPN there was no predilection towards academic providers.[17] At first, this may seem surprising, but perhaps by the time RAPN adoption was in full swing, urologists both in the private and academic settings were comfortable with the robotic platform.

The adoption of both RAPN and RALP behaved according to the Law of Diffusion of Innovation, which is a principle that describes the process and speed at which new technological advances are disseminated into society and has been validated across a wide range of disciplines. [25–28] During the innovator phase, no variables were significant factors in robotic adoption, likely due to only a few surgeons adopting an extremely novel technique. Both surgical volume and year of surgery were significant variables during the early adopter phase, which is characterized by the incorporation of new technology by key opinion leaders. [29–31] The early majority phase is characterized by surgeons who tend to adopt a new technology only after it has been successfully and consistently demonstrated by others in the field. Our analysis showed that during this phase, surgical volume had both a significant and large-magnitude effect for intermediate and high-volume surgeons, indicating that volume is the most influential factor in RAPN adoption. The highest volume providers were more likely to adopt robotic assistance than the intermediate volume surgeons, indicative of increasing consolidation of procedures among providers with the highest volumes, mirroring trends seen in RALP. [32] By the end of the early majority period, RAPN had achieved a majority share in partial nephrectomy, with a similar trend seen in RALP. [17]

Given that the highest-volume providers are most likely to adopt novel surgical techniques, focusing efforts on addressing this cohort of high-volume surgeons is essential in affecting the dissemination of technological innovation in surgical care. Ultimately, evidence-based clinical medicine requires us to carefully assess whether large-scale adoption of novel technology is appropriate by establishing a relationship between the rate of technological adoption and demonstrated clinical safety or efficacy through randomized controlled trials.

4.1 *Limitations*

This retrospective population-based analysis is not without limitations. Though our dataset has the advantage of capturing 20% of all inpatient admissions, these data were obtained through hospital sampling and are may be subject to sampling bias, although survey weighting was employed in order to mitigate this effect. Secondly, this analysis relied on CDM data in order to determine whether a procedure was performed open, laparoscopically, or robotically, as well as the presence or absence of a da Vinci robot, both of which were key components of our analysis. The reliability of this outcome variable is dependent on the accuracy of CDM coding, which may be less accurate than ICD-9 coding. Finally, the Law of Diffusion of Innovation is traditionally applied to binary outcomes, where a person has either adopted or refused to adopt a novel technology. In contrast, the adoption of robotic technology is a continuous rather than binary variable, with surgeons performing a percentage of their caseloads robotically instead of an all or nothing approach.

5. Conclusion

This retrospective population-based study sheds new evidence on the process and key factors influencing the diffusion of robotic technology for partial nephrectomies, which has not been previously described. We show that uptake of robotic technology acted according to the Law of Diffusion, with a rapid increase in adoption occurring from 2006-2008 and nearly 60% of partial nephrectomies performed robotically by 2013. The incorporation of robotic technology into the performance of partial nephrectomies occurred concurrently with consolidation towards high-volume surgeons, which were overwhelmingly more likely to utilize robotic technology. Finally, this study demonstrated that high-volume surgeons are important drivers of adoption of robotic technology into urology. These findings would be complemented by future studies correlating adoption rates with clinical outcomes or the cost-effectiveness of novel technologies within the medical field in order to determine whether rapid adoption is a patient-centered versus clinician-centered decision point.

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Abbreviations Used

RALP = Robotic-Assisted Laparoscopic Prostatectomy

RAPN = Robotic-Assisted Partial Nephrectomy

PN= Partial Nephrectomy

Table 1: Patient characteristics, hospital characteristics, and medical expenditures for PN in the USA, 2004–2013

Characteristic	Non-robotic PN		Robotic PN		P-value
Age	Percentage	95% CI	Percentage	95% CI	0.07
age<50	22%	[21-23%]	21%	[19-22%]	
age 50-59	25%	[24-27%]	26%	[25-28%]	
age 60-69	29%	[28-30%]	31%	[30-32%]	
age>=70	24%	[23-25%]	22%	[20-24%]	
Race					0.06
white	70%	[64-75%]	75%	[70-79%]	
black	9%	[8-11%]	9%	[7-11%]	
hispanic	2%	[2-3%]	1%	[0-1%]	
other	18%	[13-25%]	15%	[11-21%]	
Charlson comorbidity score					0.38
0	57%	[55-59%]	58%	[55-62%]	
1	25%	[24-26%]	24%	[23-26%]	
2	10%	[9-11%]	9%	[8-11%]	
≥3	8%	[7-10%]	8%	[6-10%]	
Teaching hospital					0.76
No	62%	[51-72%]	64%	[53-74%]	
Yes	38%	[28-49%]	36%	[26-47%]	
Hospital size					0.69
<200 beds	9%	[6-14%]	11%	[6-20%]	
200-399 beds	35%	[27-44%]	32%	[23-42%]	
>=400 beds	56%	[47-66%]	57%	[46-68%]	
Region					0.27
Midwest	22%	[15-31%]	30%	[18-44%]	
Northeast	24%	[14-36%]	17%	[10-28%]	
South	37%	[29-47%]	36%	[26-47%]	
West	17%	[11-23%]	17%	[11-26%]	
Urban					0.33
No	3%	[2-6%]	2%	[1-5%]	
Yes	97%	[94-98%]	98%	[95-99%]	

Table 2: Hospital and surgeon characteristics associated with an increased adoption rate* of robotic-assisted partial nephrectomies

	Diffusion of innovation phases		
	Innovator 2004-2005	**Early adopter 2006-2008**	**Early majority 2009-2013**
Annual partial nephrectomy volume			
Low (0-5)	Ref.	Ref.	Ref.
High (5+)	4.5%(-6.9-15.9%)	**7.0%(0.7-13.3%)***	**23.2%(16.3-30.0%)****
Teaching hospital			
No	Ref.	Ref.	Ref.
Yes	-0.4%(-2.3-1.5%)	2.8%(-3.5-9.2%)	3.6%(-5.0-12.2%)
Urban			
No	Ref.	Ref.	Ref.
Yes	1.5%(-0.4-3.4%)	-12.0%(-37.3-13.2%)	8.3%(-5.5-22.1%)
Hospital			
<200	Ref.	Ref.	Ref.
200-399	-2.7%(-11.8-6.4%)	3.7%(-3.3-10.7%)	-0.5%(-17.8-16.9%)
>400	-3.0%(-11.6-5.7%)	-1.6%(-8.1-4.8%)	0%(-17.6-17.6%)
Region			
Midwest	Ref.	Ref.	Ref.
Northeast	2.4%(-1.5-6.4%)	9.2%(-2.5-21%)	**-16.7%(-30.4--3%)***
South	0.2%(-2-2.3%)	0.1%(-4.2-4.4%)	-7%(-18.4-4.3%)
West	0.9%(-3.3-5.0%)	0.7%(-5.2-6.6%)	-4.3%(-17.0-8.4%)
Year	-0.1%(-2.8-2.7%)	**4.6%(2.4-6.7%)****	**8.6%(7.0-10.2%)****

Ref., Reference. Statistical significance: *p < 0.05, **p < 0.001.

*Surgeon adoption is defined for each individual surgeon as the number of robotic partial nephrectomies divided by the total number of partial nephrectomies in a particular year. Results of the multivariate regression analysis are reported in percent changes relative to the reference value.

Figure Legends

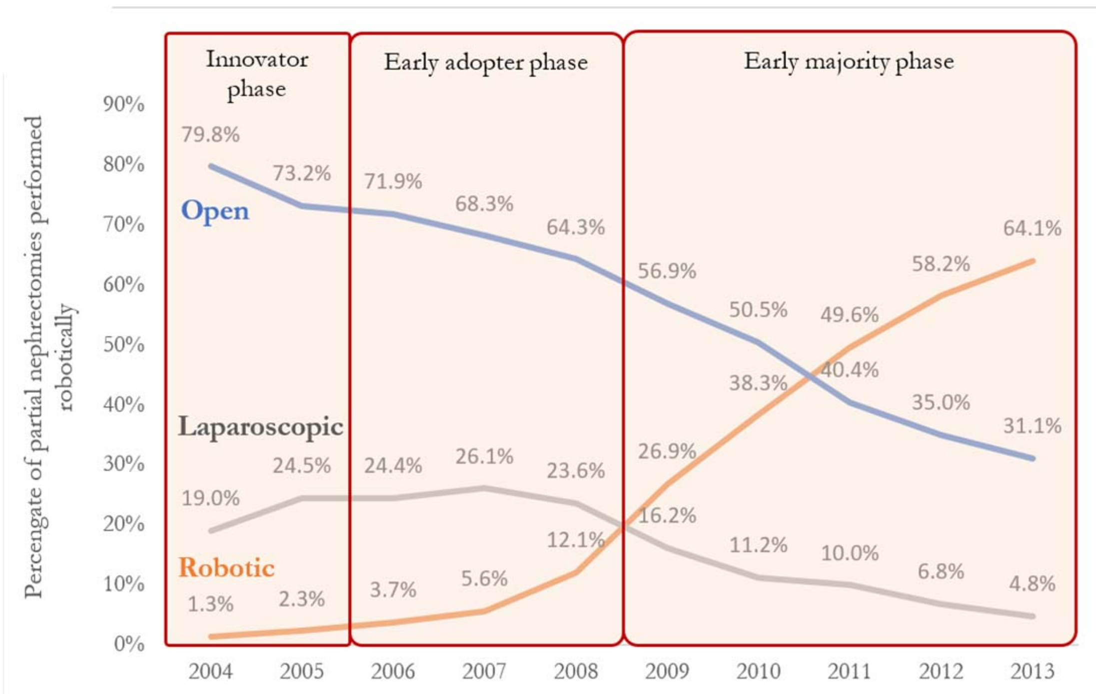

Figure 1: Trends in the adoption rates of robotic partial nephrectomies in the United States from 2003-2013, stratified by the corresponding phases of the Law of Diffusion of Innovation