Patterns of adoption of robotic radical prostatectomy in the United States and England

Laia Maynou[1,2,3,4], Winta T. Mehtsun[5,6], Victoria Serra-Sastre[2,7,8] and Irene Papanicolas[2,4,5]

[1]Department of Econometrics, Statistics and Applied Economics, Universitat de Barcelona, Barcelona, Spain

[2]Department of Health Policy, London School of Economics and Political Science, London, England

[3]Center for Research in Health and Economics, Universitat Pompeu Fabra, Barcelona, Spain

[4]OptumLabs, Eden Prairie, Minnesota, Visiting fellow

[5]Department of Health Policy and Management, Harvard T. H. Chan School of Public Health, Boston, Massachusetts

[6]Dana Farber Cancer Institute, Brigham and Women's Hospital, Massachusetts General Hospital, Boston, MA

[7]Department of Economics, City, University of London, London, England

[8]Office of Health Economics, London, England

Irene Papanicolas, PhD - **Corresponding author**
Associate Professor of Health Economics
Department of Health Policy
London School of Economics and Political Science
Houghton St, WC2A 2AE
London
Tel: +442079556472
Email: I.N.Papanicolas@lse.ac.uk

Acknowledgements

This paper was produced using Hospital Episode Statistics provided by NHS Digital under Data Sharing Agreement NIC-354497-V2J9P and using the OptumLabs Data Warehouse (OLDW). The OLDW contains de-identified retrospective administrative claims data, including medical and pharmacy claims and eligibility information as well as electronic health

record (EHR) data. This paper has been screened to ensure no confidential information is revealed.

Abstract

Objectives

To compare patterns of technological adoption of minimally invasive surgery for radical prostatectomy across the United States and England.

Data Sources

We examine radical prostatectomy in the United States and England between 2005-2017, using de-identified administrative claims data from the OptumLabs Data Warehouse in the United States and the Hospital Episodes Statistics in England.

Study Design

We conduct a longitudinal analysis of robotic, laparoscopic and open surgery for radical prostatectomy. We compare the trends of adoption over time within and across countries. Next, we explore whether differential adoption patterns in the two health systems are associated with differences in volumes and patient characteristics. Finally, we explore the relationship between these adoption patterns and length of stay, 30-day readmission, and urology follow-up visits.

Data Collection

Open, laparoscopic and robotic radical prostatectomies are identified using OPCS codes in England and ICD9, ICD10, and CPT codes in the United States.

Principal Findings

We identify 66,879 radical prostatectomies in England and 79,358 in the US during 2005-2017. In both countries, open surgery dominates until 2014, where it is overtaken by robotic surgery. The adoption of robotic surgery is faster in the United States. The adoption rates and, as a result, the observed centralization of volume, have been different across countries. In both countries, patients undergoing radical prostatectomies are older and have more comorbidities. Minimally invasive techniques show decreased length of stay and 30-day readmissions compared to open surgery. In the United States, robotic approaches were associated with lower length of stay and readmissions when compared to laparoscopic.

Conclusions

Robotic surgery has become the standard approach for radical proctectomy in the United States and England, showing decreased length of stay and in 30-day readmissions compared to open. Adoption rates and specialisation differ across countries, likely a product of differences in cost-containment efforts.

Keywords: administrative data uses, health care organizations and systems, health economics, hospitals, surgery, technology adoption/diffusion/use

Callout Box

What is known on this topic?

- Numerous studies have explored the adoption of technology within health systems, but few studies have explored the adoption of the same technology across systems.
- Little is known about the factors associated with the adoption of minimally invasive surgical techniques and robotic surgery in particular.

What this study adds?

- The initial adoption of robotic radical prostatectomy was faster in the United States as compared to England.
- Differences in adoption patterns within the two countries seem to influence the centralization of surgical volume across providers.
- The robotic approach has become the standard of care for radical prostatectomy in both countries. Robotic procedures are associated with improvements in length of stay and readmissions relative to open surgery in both countries but only show significant reductions in length of stay and readmissions relative to laparoscopic surgery in the United States.

1. Introduction

Rapid advances in medical innovation over the past decades have led to an increase in the range of alternatives for the diagnosis and treatment of disease (1–4). While these technological advances have been shown to be beneficial to care and improve outcomes, they are not always cost-effective (1,2,5). Indeed, some of the growth in health care spending across high-income countries is attributed to medical innovation (5–8). As such, policy makers across health systems have attempted to regulate technological diffusion, through the use of economic and regulatory instruments (9–11). However, little is known about how new technologies diffuse across systems with different approaches to cost-containment.

One of the recent technological developments in the area of surgery has been the introduction of minimally invasive techniques, including laparoscopic and robotic surgery. While the introduction of laparoscopic surgery has predated robotic techniques, they both confer similar patient benefits such as improved patient outcomes and faster operating and recovery times (12). However, the newer robotic techniques require a higher initial investment to purchase the robot and carry high maintenance costs. Across a spectrum of surgical conditions, laparoscopic techniques have already been adopted as the standard of care (i.e., cholecystectomy). However, for some procedures, such radical prostatectomy, robotic and laparoscopic adoption has come about more recently, and in parallel. As minimally invasive techniques become more established within systems, we can examine how they diffuse across health systems and whether we see differential uptake of the higher cost procedure (robotic) in health systems with stricter cost-containment policies. This comparative lens may offer important insights as to the factors that influence technological adoption within health systems.

In this study we explore the differential uptake of laparoscopic and robotic surgery for radical prostatectomy compared to open surgery over the past fifteen years in two countries with notably different cost-containment approaches: England and the United States (US). In England, prostatectomies provided on the National Health Service (NHS) are reimbursed based on fixed prices in hospitals operating under global budgets, while in the US, hospitals providing proctectomies do not operate under budgets and are reimbursed by multiple insurers with variable prices. The case of robotic-assisted prostatectomy is of special relevance given its widespread adoption, despite the high-fixed costs associated with it and the lack of evidence of its clinical superiority (12,13). Using the Hospital Episode Statistics (HES) data from the English NHS and de-identified administrative claims data from the OptumLabs Data Warehouse (OLDW) in the US (14), we explore three questions: 1) do we see different rates of adoption of robotic surgery for prostatectomy in England and the US; 2) do we see differences in practice associated with differential uptake of this technology and, 3) are different adoption patterns associated with improvements in key surgical outcomes such as length of stay (LoS), 30-day readmission, and the number of urology follow-up visits?

2. Methods

2.1.Data

To examine the uptake of robotic surgery in England, we used HES, an administrative dataset that records all in-hospital admissions in the English NHS. For the US, we used de-identified administrative claims data from the OLDW (14), which includes longitudinal health information on enrolees with health coverage from commercial and Medicare Advantage (MA) plans. This data represents a diverse mixture of ages, race/ethnicities and geographical regions which are similar to the characteristics of the national US population (15).

From both datasets we extracted all admissions related to radical prostatectomies between 2005-2017 and disaggregate them by type of approach: open, laparoscopic and robotic. In England, the admissions were identified by extracting all patients with a prostatectomy procedure code as their main operation, using the Office of Population Censuses and Surveys Classification of Interventions and Procedures (OPCS-4) codes. In the US, admissions were identified using ICD9, ICD10 Procedure Coding System (PCS) and the Current Procedural Terminology (CPT) codes (Appendix Table A1). Emergency and elective admissions were included for each country as it was not possible to distinguish the admission type in the US data. In England, 99.5% of procedures were elective. In the US data, any admission not linked to a hospital was excluded (7,155 patients, 8.2% of the sample). For 2,112 patients undergoing a minimally invasive procedure we could not differentiate type of procedure. We excluded these patients when doing any analysis that required a distinction between robotic and laparoscopic surgery.

Appendix Table A2 shows the yearly prostatectomy volume in the OLDW, relative to a representative sample of national volumes as measured by the National Inpatient Sample (NIS). According to these figures, our sample captured a consistent proportion of the NIS volume over time (~8%). The table also illustrates the proportion of the sample enrolled in MA over the study period and how this compares to national enrolment. Over time the proportion of MA patients in the sample increased, but at a faster rate than national trends. For this reason, we carry out all the US analysis separately for commercial insurance and MA patients.

Our data included information on patient characteristics including age, race, comorbidity and socio-economic status. Age and comorbidities were available in both datasets. To adjust for patient comorbidity we used the Charlson Comorbidity Index (16) and counts of specific secondary diagnosis: diabetes, circulatory disease, respiratory disease and mental health. Selfreported race/ethnicity was reported in the HES data, while the OLDW includes third-party race/ethnicity data estimated using individual's name and geographic location. Different measures of socio-economic status were available in the two datasets. HES data reported values of the Index of Multiple Deprivation (IMD) for each patient, assigned based on the patient postcode. The IMD measures relative levels of deprivation in 32,844 small areas in England. Each area is allocated an IMD quintile according to the proportion income deprivation, with the first decile indicating the most deprived areas (17). OLDW includes household yearly income estimated from a third-party model using both public and private consumer data (credit card statements and loans). This variable was assigned at the household level, where all individuals within the same household would be assigned the same income value (*<40,000, 40,000-74,900, 75,000-124,900, 125,000-199,900, >200,000*). As variables on race/ethnicity and income were not directly comparable, we only used them in the sensitivity analysis.

The OLDW data also contained information on the reimbursement. In England, NHS providers are reimbursed a fixed price corresponding to an assigned Health-Related Group (HRG), which is allocated to all hospitalized patients based on their procedure, diagnosis, age and level of complication. HRGs are linked to fixed tariffs, which are derived from average hospital costs and are updated annually (18). Using each patient's assigned HRG code we identified the reimbursement rate, which was converted to 2017 US dollars using the OECD AIC Purchasing Power Parity index (Appendix Table A3).

We also extracted data on a range of surgical outcomes: LoS, 30-day readmission and the number of urology follow-up visits within a year after surgery. We included follow-up visits as a proxy for unresolved complications that might arise post-surgery requiring further visits to a specialist.

2.2.Methods

First, we compared the relative uptake of different approaches for prostatectomy over time by constructing a longitudinal panel for each country. We plotted the total volume of each procedure over the period 2005-2017, looking at minimally invasive approaches and also laparoscopic and robotic-assisted approaches, separately. Next, we plotted the number of hospitals performing each procedure, each year.

Second, we explored the characteristics of patients receiving each of the procedures, and their surgical outcomes, including LoS, 30-day readmission rates and the number of urology follow-up visits between 2005-2017. For the US, we explored the characteristics separately for the commercial and MA populations. To determine whether certain patients are more likely to receive a specific procedure, we also ran a multivariate regression with type of surgery as the dependent variable and age, sex and comorbidity as independent variables.

Finally, we examined the relationship between adoption patterns and the three surgical outcomes. To examine this relationship, we used a multivariate patient-level linear regression model run separately for the commercial and MA patients [1], controlling for age and comorbidity, with hospital fixed-effects and time trends. Although the outcomes were discrete and binary, we chose linear models to preserve the interpretability of linear trends.

$$Y_{ijt} = \alpha + \beta surgery_{ijt} + \gamma X_{ijt} + H_j + T_t + \mu_{ijt} \quad [1]$$

Y_{ijt} indicates each outcome, for patient i, treated in hospital j in year t (2005 to 2017); $surgery_{ijt}$ denotes a set of binary variables indicating whether the surgical approach was open, laparoscopic or robotic; X_{ijt} is a vector of covariates (Charlson Comorbidity Index and age); H_j denotes hospital fixed-effects; T_t is a linear time trend; α, β and γ are unknown parameters and μ_{ijt} is the normally distributed disturbance term. In our sensitivity analyses, we present the results using 1) individual comorbidities variables instead of the Charlson Comorbidity Index, 2) an extended set of covariates (including race and socio-economic status) and 3) using Poisson and Logit models.

Statistical analysis was conducted using Stata 15 (College Station, TX, USA).

3. Results

Our sample comprised of 66,879 patients in England and 79,358 patients in the US who underwent a radical prostatectomy between 2005-2017 (Table A2). In 2017, there were 7,705 patients in England and 7,124 in the US (60.8% commercial and 39.2% MA) (Table 1). In 2017, the US performed a higher proportion of open and laparoscopic surgeries, while England had a higher proportion of robotic surgeries. In England, 91.5% of patients underwent a minimally invasive procedure, with robotic techniques accounting for 85.1% of the total. In the US, 88.7% of commercial patients and 83.9% of MA patients had a minimally invasive procedure, of which 78.1% and 62% of the total had a robotic procedure, respectively. Prostatectomy patients were treated in 59 hospitals in England compared to 1,297 in the US. On average, across countries the patients had a similar age (around 64 years). A higher proportion of English patients were white. Patient comorbidity as measured by the Charlson Comorbidity Index was similar across the two countries. When disaggregating by disease group, however, we observed a higher proportion of patients in all comorbidity categories in the US compared to England. In England, most patients belonged to the less deprived category, while in the US most patients belonged in the middle-income category (75,000-124,900). The mean reimbursement for radical prostatectomy for 2017 was $8,249.24 in England, $18,799.91 for commercial patients and $9,412.49 for MA.

Appendix Table A4 shows these descriptive statistics for the baseline year, 2005. The total volume for radical prostatectomy was lower for both countries: 3,257 patients in the US sample (95.9% commercial and 4.1% MA), and 4,798 in England. In both, the dominant surgical technique was open prostatectomy. Minimally invasive procedures accounted for 10.3% in England, and 8.5% for commercial and 4.6% for MA in the US. 120 hospitals carried out prostatectomies in England, double the 2017 number, and 1,139 hospitals performed the procedure in the US, fewer than in 2017. Patients in both countries were younger and healthier as compared to 2017. The reimbursement level was also lower in 2005, averaging $5,155.94 in England and in the US $11,031.56 for commercial and $7,131.00 for MA.

3.1. Volumes over time

Figure 1 shows the aggregate volumes of each procedure over time per country. In both countries, open surgery had the highest volumes until 2009 (2,431 in England in 2009 and 5,031 in the US in 2008). From 2010 minimally invasive approaches overtook open approaches, reaching 7,049 in England and 6,184 in the US in 2017. In both countries, this increase was driven by robotic approaches; while laparoscopic volumes were lower than both robotic and open approaches over the full period. In the late 2000s, the uptake of robotic surgery was faster in the US compared to England, but similar levels of diffusion were reached by

2014. Appendix Figure A1 illustrates the trends for each surgical approach over time and Figure A2 illustrates these trends separately for commercial and MA. For both groups, the overall trend was the same with open procedures dominating till 2009 after which minimally invasive took over, driven by robotic.

Figure 2 shows the number of hospitals that performed each procedure, by year. This figure better illustrates the extent to which the increase of robotic volume is driven by small increases across all providers or large increases in a few providers. In 2005, most hospitals in both countries performed open radical prostatectomy (80% in England and 92% in the US), followed by laparoscopic procedures (19% in England and 8% in the US), and with almost no robotic procedures in either country. By 2017, the number of hospitals performing any prostatectomy fell in England, while it increased in the US. Of these providers, the proportion offering open prostatectomy decreased to 48% in England and 29% in the US. In England the proportion of hospitals performing laparoscopic surgery in 2017 decreased to 8%, while in the US this increased to 13%. The total number of hospitals performing robotic surgery increased in both countries over time, representing 43% of hospitals in England and 58% in the US by 2017.

3.2. Changes of patient characteristics and outcomes

Over the study period, the mean age of the patients undergoing radical prostatectomy increased in both countries (Table 2). The age increase was more pronounced in the US for laparoscopic (4.2 years commercial, 5.5 years MA vs. 1.4 years in England) and open (1.2 years commercial, 3.7 years MA vs. 2.6 years in England) approaches. The average age of patients undergoing robotic prostatectomy also increased in England (2.9 years) and the commercially insured (1.1

years), while it decreased for MA patients (1.5 years). In both countries, over time, the mean comorbidity of patients increased except for laparoscopic surgery in the US. The largest increase in the Charlson Comorbidity Index was observed for open prostatectomy (0.4 points in England, 0.4 commercial and 0.9 MA). In the US, average reimbursement for open prostatectomy increased over the time period by $12,268.74 for commercial and $6,774.29 for MA. Reimbursement for robotic and laparoscopic prostatectomy increased by $7,364.26 and $4,857.78 for commercial patients, and decreased for MA patients by $2878.79 and $537.15, respectively.

Over the study period, LoS decreased for all surgical approaches in England and increased in the US, although starting from a lower baseline. In 2017, open prostatectomy had the highest LoS for both countries (3.4 days in England, 4.4 days for commercial and 7.1 days for MA), and robotic prostatectomy had the lowest (1.6 days in England, 2.0 for commercial and 2.2 for MA). We observed an increase in 30-day readmissions across all three approaches, in both countries. Finally, we observed an increase in the number of follow-up urology visits in both countries, apart from open prostatectomy in the US.

To complement these trends, we report the association between surgical approach and patient characteristics over time in Table A5. In both countries, over time, open radical prostatectomy was performed on an older and more comorbid population, with minimally invasive approaches performed on increasingly younger and healthier patients.

3.3. Surgical outcomes by type of procedure

Table 3 shows the association between hospital adoption patterns and outcomes. Minimally invasive approaches were associated with approximately a 1-day reduction in LoS relative to open prostatectomy in England and the US commercial patients. For MA patients this reduction was nearly 2-days. Similarly, minimally invasive surgery was associated with a reduction in 30-day readmissions, of 1.4% in England, 1.0% in the commercial US sample and 2.9% in the MA sample, relative to open surgery. When compared to open surgery, minimally invasive approaches were not significantly related to the number of follow-up visits, apart for the commercial US sample were they decreased, although by a negligible magnitude.

When we examine laparoscopic and robotic approaches compared to open prostatectomy, the reduction in LoS and readmissions is statistically significant in England. In the US, LoS and readmission for robotic procedures declined in both commercial and MA groups. However, LoS for laparoscopic approaches only significantly decreased for the commercial patients. While there were no significant changes to follow-up visits for robotic patients in either country, we saw a significant increase in visits following laparoscopic surgery in England and a decrease in follow-up visits for both insurance groups in the US. Older patients had higher LoS, and a lower number of follow-up visits in both countries. In the US, older patients with commercial insurance had lower readmissions rates, while older patients with MA had higher readmission rates.

When comparing robotic versus laparoscopic outcomes, results showed no improvements of robotic approaches over laparoscopic in England. However, in the US, the improvements were seen in LoS and 30-day readmission rates for both commercial and MA patients, although of a much greater magnitude in MA. Follow-up visits also increased for MA patients after robotic surgery, relative to laparoscopic.

3.4.Sensitivity analysis

Table A6 used individual comorbidity variables instead of the Charlson Comorbidity Index and results are in line with the main specification. Table A7 used an extended set of covariates including race/ethnicity and socio-economic status and results are also in line with the main specification. Higher socio-economic status was associated with significantly lower LoS in both countries, lower 30-day readmissions in the US and more follow-up visits in the US. Being black was related to an increase in LoS and in the number of follow-up visits for England and commercial insurance patients in the US. Black patients were more likely to be readmitted relative to white patients in England. Table A8 estimates the coefficients using Poisson models for LoS and number of follow-up visits and Logit regression for the 30-day readmission. Results showed similar results to the main specification, but the magnitude of the effect was smaller for LoS and the number of follow-up visits, and larger for 30-day readmissions (apart for MA patients where it was not significant).

4. Discussion

In this study we explored the differential uptake of minimally invasive approaches for radical prostatectomy in England and the US over the past fifteen years. Over the study period, minimally invasive approaches, and in particular robotic prostatectomy, replaced open prostatectomy as the standard of care in both countries. The initial uptake of robotic prostatectomy was faster in the US as compared to England, but through a more gradual uptake

England reached similar levels of adoption by 2014. While rates of adoption at the end of the study period are similar at the national level, there are meaningful differences in the degree of hospital specialisation within countries, which we believe is related to differences in cost-containment approaches. In both countries, over time, open radical prostatectomy is being performed on an older and more comorbid population, with minimally invasive approaches performed on the relatively younger and healthier patients. We find that minimally invasive approaches are associated with reductions in inpatient LoS and 30-day readmissions rates compared to open prostatectomy. In the US, robotic approaches outperform laparoscopic, although this is not the case in England.

Our results raise important questions for policy makers interested in understanding the drivers and impact of diffusion of new technologies across different health systems. In this study we observe differential uptake of minimally invasive approaches in England and the US, with an initial faster rate of adoption in the US. While there are many differences between the two health systems it is likely that the differential uptake of robotic prostatectomy is related to differences in reimbursement of hospital providers, which has been observed for other types of technologies. In this paper, we examine data from two health systems: the NHS, which relies on fixed prices, and a database of commercially insured and MA patients in the US, which captures variable prices. Mostly likely as a product of these reimbursement structures, we observe large differences in the average expenditure for this procedure across the two countries, with the US spending almost consistently double the dollar amount relative to England. Interestingly, there is also a large difference in the average reimbursement between commercial insurance and MA in the US; where commercial spending is almost double MA for all procedures. This is likely related to the need for insurance to compete with Medicare fee-for-service prices which are lower and fixed. This raises questions about whether higher prices in commercial insurance subsidise technological adoption for the Medicare populations, or whether there are potential efficiency gains to be made in commercial insurance.

The Technological Change in Health Care Research Network (9), found the type of provider payment to be a key factor influencing the rate of adoption, particularly for new technologies with high fixed costs, where systems using fixed provider payments experienced relatively little growth in use of invasive procedures over time (9,19). Robotic surgery has high fixed costs – the purchase of the robot and maintenance costs– which likely influences the differential uptake of the approach in the US and England. In England robots were purchased and used mainly for radical prostatectomy, which is among the most high-volume robotic procedure in the country. While in the US robots have been used across a wider range of clinical specialties (20), which may explain the rapid uptake of the technology in the US if providers already had robots on site. In the US hospitals are also likely to have funds to purchase these high-cost technologies, or even to factor this into price negotiations. However, in England, NHS hospitals' need the approval of the hospital's Board of Directors and the relevant Clinical Commissioning Group to purchase this technology (21). Even with approvals granted, NHS hospitals need to raise funds to purchase the robot, which is commonly done through charities or leasing agreements (21,22). As a result, fewer hospitals in England are able to offer robotic surgery, yet those who do offer high volumes.

Our results suggest that differential robotic adoption across hospitals not only influences volumes of robotic procedures but may also be related to the degree of procedural specialization across these two health care systems. Notably, in England, over the study period, the number of hospitals providing any type of surgery for prostatectomy halves, and nearly all prostatectomies are provided by hospitals who purchased the robotic technology and thus have the ability to offer any of the three approaches. In contrast in the US, we observe an increase in the number of hospitals providing prostatectomies, with the increase being mostly driven by the hospitals offering robotic approaches. Comparatively fewer hospitals continue to carry out open prostatectomy, suggesting that open approach is becoming centralized to a greater degree.

Our analysis also shows that as the robotic approach for radical prostatectomy is becoming more widespread, standard practices are changing. Over time, all three approaches are being performed on patients that are older and have more comorbid conditions. However, robotic prostatectomy is replacing open approaches, for younger and healthier patients, while open prostatectomy is reserved for more clinically frail and complex patients. While these changes in practice are observed for both countries, they are more pronounced in the US, across both commercial insurance and MA. It is likely that as fewer hospital providers carry out open prostatectomy, and more offer robotic approaches, open surgery is reserved for a comparatively older and clinically complex population in the US than in England where the same hospitals offer all three procedures.

Previous literature has shown that minimally invasive procedures have better surgical outcomes than open procedures (12,13,23–25). Our results support this and show that minimally invasive procedures are associated with improvements in LoS and 30-day readmissions rates in both countries relative to open surgery. While in the US, the improvements in LoS and 30-day readmission rates were driven by robotic surgery, in England the differences are quantitatively similar for both laparoscopic and robotic surgery, compared to open procedures. When we compare the same outcomes between robotic and laparoscopic approaches, we find that robotic procedures are associated with improvements in LoS and readmissions, although only for the US.

To the best of our knowledge, this is the first paper that provides a comparative analysis of adoption rates of minimally invasive surgery across countries. This paper contributes to two main themes of the literature. First, in the field of diffusion of medical innovation. Previous literature has shown that while medical innovation increases health care expenditure, it also shows improvements in surgical outcomes and quality of life (1–6,8,9). Our results are in line with this research, as robotic surgery has a high initial investment, but it comes with centralization of care and efficency gains. Furthermore, we compare the adoption rates of robotic surgery of two countries, showing that fixed or variable prices may influence the rates of adoption. Second, we also contribute to the specific literature on robotic surgery improvement in outcomes. Our results are in line with previous literature showing that robotic approaches are associated with better surgical outcomes than open procedures (12,13). We also find that in the US robotic surgery is associated with improved outcomes compared to laparoscopic approaches.

Our study had several limitations. First, for the US, we relied on the OLDW de-identified administrative claims data, only captures the enrolled individuals, thus will not capture the total volume of procedures performed by individual hospitals or surgeons. However, the OLDW database represents a diverse mixture of ages, ethnicities and geographical regions across the US which has been shown to be similar to that of the national population (15). To account for possible changes in the national representativeness of the MA population we stratified all analysis, and report results for this population separately. For England, representativeness was less of a concern as the data included all patients admitted for radical prostatectomy in the NHS (only 10% of the English population has supplemental private insurance (26)). Second, although the study does not claim causality, the trends and associations shown are relevant to explain the uptake of this new technology. Third, there were missing values in some of the patient-level characteristics which reduced the sample size. We ran additional models in the sensitivity analysis, with very similar results to our base specification. Fourth, we did not have access to additional outcome data including oncologic outcomes, complications, quality of life, and overall survival, which are relevant to this population. Finally, for the US, we did not have access to individual provider or hospital characteristics, so, we were unable to control for these. We used hospital fixed-effects to try to account for these characteristics as much as possible.

Over the past fifteen years the robotic approach has become the standard of care for radical prostatectomy in both England and the US. The adoption rates and, as a result, the observed centralization of volume, have been different across countries, likely a product of differences in cost containment efforts within the two systems. Although we show evidence of improvements in surgical outcomes associated with the robotic procedure, the differences in diffusion and specialisation across the two countries suggest that these may translate into variable effects on surgical practice and hospital outcomes that become more pronounced over time.

CONFLICT OF INTEREST

All authors declare no competing interests.

AUTHOR CONTRIBUTIONS

All authors conceived the study. Laia Maynou and Irene Papanicolas developed the methodological approach and wrote the first draft of the manuscript. Laia Maynou accessed the data and did the analysis. Winta T. Mehtsun and Victoria Serra-Sastre did the literature review. All authors contributed to interpretation of the data and critical revision of the manuscript and approved the final version.

DATA AVAILABILITY STATEMENT

Retrospective, de-identified administrative data were obtained from Hospital Episode Statistics provided by NHS Digital under Data Sharing Agreement NIC-354497-V2J9P and from OptumLabs® Data Warehouse (OLDW). The OLDW contains de-identified retrospective administrative claims data including medical and pharmacy claims and eligibility information as well as electronic health record (EHR). Data were provided under a data sharing agreement which prohibits onward sharing.

ORCID

Laia Maynou https://orcid.org/0000-0002-0447-2959

Victoria Serra-Sastre https://orcid.org/0000-0002-6329-4507

Irene Papanicolas https://orcid.org/0000-0002-8000-3185

References

1. Cutler DM, McClellan M. Is Technological Change In Medicine Worth It? Health Aff. 2001;20(5):11–29.
2. Skinner J, Staiger D. Technology Diffusion and Productivity Growth in Health Care. Rev Econ Stat. 2015;97(5):951–64.
3. Lamiraud K, Lhuillery S. Endogenous Technology Adoption and Medical Costs. Health Econ. 2016;25(9):1123–47.
4. Naanaa ID, Sellaouti F. Technological Diffusion and Growth: Case of the Tunisian Manufacturing Sector. J Knowl Econ. 2017;8(1):369–83.
5. Cutler DM, Rosen AB, Vijan S. The Value of Medical Spending in the United States, 1960–2000. N Engl J Med. 2006;355(9):920–7.
6. Newhouse JP. Medical Care Costs: How Much Welfare Loss? J Econ Perspect. 1992 Sep;6(3):3–21.
7. Smith S, Newhouse JP, Freeland MS. Income, insurance, and technology: why does health spending outpace economic growth? Health Aff (Millwood). 2009;28(5):1276–84.
8. Chandra A, Skinner J. Technology Growth and Expenditure Growth in Health Care. J Econ Lit. 2012 Jul;50(3):645–80.
9. McClellan M, Kessler D, for the TECH Investigators. A Global Analysis Of Technological Change In Health Care: The Case Of Heart Attacks. Health Aff. 1999;18(3):250–5.
10. Romeo AA, Wagner JL, Lee RH. Prospective reimbursement and the diffusion of new technologies in hospitals. J Health Econ. 1984;3(1):1–24.
11. Cappellaro G, Ghislandi S, Anessi-Pessina E. Diffusion of medical technology: The role of financing. Health Policy (New York). 2011;100(1):51–9.
12. Moran PS, O'Neill M, Teljeur C, Flattery M, Murphy LA, Smyth G, et al. Robot-assisted radical prostatectomy compared with open and laparoscopic approaches: A systematic review and meta-analysis. Int J Urol. 2013 Mar 1;20(3):312–21.
13. Nossiter J, Sujenthiran A, Charman SC, Cathcart PJ, Aggarwal A, Payne H, et al. Robot-assisted radical prostatectomy vs laparoscopic and open retropubic radical prostatectomy: functional outcomes 18 months after diagnosis from a national cohort study in England. Br J Cancer. 2018;118(4):489–94.
14. OptumLabs. OptumLabs and OptumLabs Data Warehouse (OLDW) Descriptions and Citation. Eden Prairie, MN n.p. (PDF):Reproduced with permission from OptumLabs.
15. Jeffery MM, Hooten WM, Henk HJ, Bellolio MF, Hess EP, Meara E, et al. Trends in opioid use in commercially insured and Medicare Advantage populations in 2007-16: retrospective cohort study. BMJ. 2018;362:k2833.
16. Charlson ME, Pompei P, Ales KL, MacKenzie CR. A new method of classifying prognostic comorbidity in longitudinal studies: Development and validation. J Chronic Dis. 1987;40(5):373–83.
17. Ministry of Housing Communities & Local Government. The English indices of deprivation 2015 [Internet]. 2015. Available from: https://www.gov.uk/government/statistics/english-indices-of-deprivation-2015
18. Mason A, Ward P, Street A. England: The Healthcare Resource Group System. In: Busse R, Geissler A, Quentin W, Wiley M, editors. Diagnosis Related Groups in Europe Moving Towards Transparency, Efficiency and Quality in Hospitals. Maidenhead: Open University Press.; 2011.

19. Bech M, Christiansen T, Dunham K, Lauridsen J, Lyttkens CH, McDonald K, et al. The influence of economic incentives and regulatory factors on the adoption of treatment technologies: a case study of technologies used to treat heart attacks. Health Econ [Internet]. 2009 Oct 1;18(10):1114–32. Available from: https://doi.org/10.1002/hec.1417
20. Sheetz KH, Claflin J, Dimick JB. Trends in the Adoption of Robotic Surgery for Common Surgical Procedures. JAMA Netw Open. 2020 Jan 10;3(1):e1918911–e1918911.
21. Murphy D, Dasgupta P, Murphy I. Can the NHS afford robotic surgery? Clin Serv J. 2009;18:37–9.
22. Sandhu J. 'Robosurgeons vs. robosceptics': can we afford robotic technology or can we afford not to? J Clin Urol. 2018 Dec 11;12(4):285–95.
23. Hu JC, Wang Q, Pashos CL, Lipsitz SR, Keating NL. Utilization and Outcomes of Minimally Invasive Radical Prostatectomy. J Clin Oncol. 2008 May 10;26(14):2278–84.
24. Hu JC, Gu X, Lipsitz SR, Barry MJ, D'Amico A V, Weinberg AC, et al. Comparative effectiveness of minimally invasive vs open radical prostatectomy. JAMA. 2009;302(14):1557–64.
25. Gandaglia G, Sammon JD, Chang SL, Choueiri TK, Hu JC, Karakiewicz PI, et al. Comparative Effectiveness of Robot-Assisted and Open Radical Prostatectomy in the Postdissemination Era. J Clin Oncol. 2014 Apr 14;32(14):1419–26.
26. Papanicolas I, Woskie LR, Jha AK. Health Care Spending in the United States and Other High-Income Countries. JAMA [Internet]. 2018 Mar 13;319(10):1024–39. Available from: https://doi.org/10.1001/jama.2018.1150

Tables and Figures

Table 1: Sample Characteristics for England and the United States (2017)

Patient Characteristics	**England**	**United States**	
		Commercial (COM)	**Medicare Advantage (MA)**
No. of patients	7,705	4,333 (60.8%)	2,791 (39.2%)
No. of hospitals*	59	971	855
Open	656 (8.5%)	491 (11.3%)	449 (16.1%)
Minimal Invasive	7,049 (91.5%)	3,842 (88.7%)	2,342 (83.9%)
Laparoscopic	489 (6.4%)	406 (9.9%)	597 (21.7%)
Robotic	6,560 (85.1%)	3,198 (78.1%)	1,703 (62.0%)
Age in years, mean (standard deviation)	64 (7)	61 (7)	71 (6)
Race (%)			
White	5,077 (92.1%)	2,492 (79.5%)	1,885 (71.6%)
Black	233 (4.2%)	296 (9.5%)	388 (14.7%)
Other	201 (3.7%)	344 (11.0%)	362 (13.7%)
Comorbidity (%)			
Charlson Comorbidity Index (mean)	2.37	2.45	2.64
Diabetes	622 (8.1%)	633 (14.6%)	620 (22.2%)
Circulatory Disease	3114 (40.4%)	2,297 (53.0%)	1,876 (67.2%)
Respiratory Disease	861 (11.2%)	404 (9.3%)	398 (14.3%)
Mental Health	906 (11.8%)	712 (16.4%)	472 (16.9%)
Socio-economic status (%)			
Socio-economic status 1 (lower)	1,112 (15%)	303 (10.3%)	527 (20.4%)
Socio-economic status 2	1,156 (15.7%)	598 (20.3%)	800 (31.0%)
Socio-economic status 3	1,285 (17.4%)	888 (30.1%)	814 (31.5%)
Socio-economic status 4	1,824 (24.7%)	638 (21.7%)	314 (12.1%)
Socio-economic status 5 (higher)	2007 (27.2%)	517 (17.6%)	129 (5.0%)
Reimbursement (mean) (in US dollars)	$8,249.24	$18,799.91	$9,412.49

Notes: *White in the US sample represents the non-Hispanic whites (Hispanics are in others), Socio-economic status in England is represented by the Index of Multiple Deprivation and in US is represented by household income levels (<40,000,40,000-74,900, 75,000-124,900, 125,000-199,900, >200,000). *US hospitals treated both type of enrolled patients (commercial and MA) being the total number of hospitals 1,297. The proportion of laparoscopic and robotic do not sum up to the proportion of minimally invasive because the CPT was missing and we could not differentiate between laparoscopic and robotic.*

Table 2. Characteristics of Patients Undergoing Open, Laparoscopic, and Robotic Radical Prostatectomy in England and the United States

		Open			Minimally Invasive			Laparoscopic			Robotic		
		England	**US (COM)**	**US (MA)**	**England**	**US (COM)**	**US* (MA)**	**England**	**US (COM)**	**US* (MA)**	**England**	**US (COM)**	**US* (MA)**
Age (in years)	*2005*	62.2	60.4	68.7	62.4	59.7	68.8	62.4	59.7	68.8	60.7	59.2	71
	2017	64.8	61.6	72.4	63.6	60.6	70.7	63.8	63.9	74.3	63.6	60.3	69.5
Charlson Comorbidity Index	*2005*	2.1	2.3	2.4	2.2	2.3	2.4	2.2	2.3	2.4	2.2	2.3	2.5
	2017	2.5	2.7	3.3	2.4	2.4	2.5	2.4	2.1	2.2	2.4	2.4	2.6
Reimbursement (US dollars)	*2005*	-	10,983.38	6,971.31	-	11,552.04	10,413.43	-	11,711.15	10,413.43	-	11,026.65	11,146.39
	2017	-	23252.12	13,745.6	-	18,231.62	8,581.6	-	16,568.93	9,876.28	-	18,390.91	8,267.60
Length of stay (days)	*2005*	6.3	2.6	2.9	4.5	1.9	1.4	4.5	1.9	1.4	3.5	1.3	2.5
	2017	3.4	4.4	7.1	1.6	2.1	2.8	2.1	3.1	4.7	1.6	2.0	2.2
30-day readmissions (%)	*2005*	9.9%	4.0%	3.2%	10.4%	4.3%	22.2%	10.4%	4.3%	22.2%	9.0%	5.0%	0.0%
	2017	17.5%	12.4%	15.1%	10.8%	6.7%	6.8%	13.3%	7.9%	11.9%	10.6%	6.8%	4.8%
Follow-up urology visits (1 year) (number)	*2005*	1.1	3.2	3.7	1.0	2.9	3.3	1.0	2.8	3.3	1.0	2.2	3
	2017	3.5	2.8	2.7	4.0	3.0	3.4	4.7	2.6	3.1	3.9	3.0	3.5

*Notes: The table reports the patient characteristics' mean for each surgery type, year and country. For robotic, the mean of 2005 is from 2006. Reimbursement for England not shown given there is practically no variation in the tariffs used to reimburse hospitals for each procedure type. COM= commercial insurance, MA= Medicare Advantage. *number of observations for 2005/2006 are <11.*

Table 3: Association of surgical approach with key outcomes by country, 2005-2017

	LoS			30-Day Readmission			Follow-up Visits		
Panel 1: Open (reference category) vs Minimally Invasive									
	England	**US (COM)**	**US (MA)**	**England**	**US (COM)**	**US (MA)**	**England**	**US (COM)**	**US (MA)**
Minimally Invasive	-1.224***	-0.771***	-1.808***	-0.014***	-0.009***	-0.029***	0.204	-0.076**	0.084
	(0.119)	(0.052)	(0.289)	(0.005)	(0.003)	(0.006)	(0.134)	(0.039)	(0.077)
Age	0.014***	0.017***	0.073***	0.0003	-0.001***	0.003***	-0.017***	-0.015***	-0.013**
	(0.002)	(0.002)	(0.010)	(0.0002)	(0.0001)	(0.001)	(0.003)	(0.002)	(0.006)
Comorbidity	0.217***	0.262***	0.643***	0.012***	0.022***	0.029***	0.051**	0.091***	0.002
	(0.025)	(0.020)	(0.060)	(0.002)	(0.002)	(0.002)	(0.026)	(0.015)	(0.021)
N	65,297	66,592	12,766	66,753	66,592	12,766	66,753	66,592	12,766
Hospitals	141	2,436	1,551	141	2,436	1,551	141	2,436	1,551
Mean outcome	3.04	2.12	2.85	10.8%	5.6%	5.7%	3.76	3.14	3.35
Panel 2: Open (reference category) vs Robotic and Laparoscopic									
	LoS			**30-Day Readmission**			**Follow-up Visits**		
	England	**US (COM)**	**US (MA)**	**England**	**US (COM)**	**US (MA)**	**England**	**US (COM)**	**US (MA)**
Robotic	-1.194***	-0.896***	-2.118***	-0.019***	-0.012***	-0.037***	-0.251	-0.069*	0.144*
	(0.160)	(0.056)	(0.268)	(0.007)	(0.003)	(0.006)	(0.231)	(0.041)	(0.083)
Laparoscopic	-1.250***	-0.269***	0.116	-0.010**	0.001	0.009	0.597***	-0.113**	-0.260**
	(0.115)	(0.068)	(0.518)	(0.005)	(0.005)	(0.011)	(0.146)	(0.057)	(0.117)
Age	0.014***	0.016***	0.047***	0.0003*	-0.001***	0.002***	-0.016***	-0.015***	-0.009
	(0.002)	(0.002)	(0.012)	(0.0002)	(0.0001)	(0.001)	(0.003)	(0.002)	(0.006)
Comorbidity	0.217***	0.271***	0.666***	0.012***	0.022***	0.029***	0.050*	0.094***	-0.004
	(0.025)	(0.020)	(0.063)	(0.002)	(0.002)	(0.002)	(0.025)	(0.016)	(0.021)
N	65,297	64,649	12,597	66,753	64,649	12,597	66,753	64,649	12,597
Hospitals	141	2,427	1,546	141	2,427	1,546	141	2,427	1,546
Mean outcome	3.04	2.14	2.89	10.8%	5.6%	5.7%	3.76	3.14	3.34
Panel 3: Laparoscopic (reference category) vs Robotic									
	LoS			**30-Day Readmission**			**Follow-up Visits**		
	England	**US (COM)**	**US (MA)**	**England**	**US (COM)**	**US (MA)**	**England**	**US (COM)**	**US (MA)**
Robotic	-0.261	-0.562***	-2.048***	-0.002	-0.014**	-0.049***	-0.238	0.076	0.380***
	(0.187)	(0.068)	(0.271)	(0.008)	(0.006)	(0.010)	(0.264)	(0.060)	(0.135)
Age	0.008***	0.014***	0.033***	0.0001	-0.0004**	0.002***	-0.015***	-0.014***	-0.006
	(0.001)	(0.002)	(0.001)	(0.0002)	(0.0002)	(0.001)	(0.004)	(0.003)	(0.007)
Comorbidity	0.173***	0.171***	0.534***	0.011***	0.022***	0.028***	0.052**	0.108***	0.034
	(0.029)	(0.023)	(0.057)	(0.002)	(0.002)	(0.003)	(0.025)	(0.024)	(0.030)
N	42,102	35,723	8,924	42,714	35,723	8,924	42,714	35,723	8,924
Hospitals	81	1,467	1,200	81	1,467	1,200	81	1,467	1,200
Mean outcome	2.17	1.84	2.51	10.3%	5.8%	5.1%	3.76	3.10	3.36

*Notes: Standard errors clustered at hospital-level in parentheses. Significance levels: *** p<0.01, ** p<0.05, * p<0.1. Models adjusted for Hospital Fixed-effects and year trends. The period of analysis is 2005-2017 for both panels. COM= commercial insurance, MA= Medicare Advantage.*

Figure 1: Trends for Open, Laparoscopic and Robotic Radical Prostatectomy in England and the United States (2005-2017)

(I) – England *(II) – US*

Figure 2: Number of Hospitals Performing Open, Laparoscopic, and Robotic Radical Prostatectomy in England and the United States (2005-2017)

(I) – England *(II) – US*