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The diffusion of robotic surgery: Examining technology use in the English NHS

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ABSTRACT

This paper examines the adoption and diffusion of medical technology as associated with the dramatic recent increase in the surgical use of robots. We consider specifically the sequential adoption and diffusion patterns of three interrelated surgical technologies within a single healthcare system (the English NHS): robotic, laparoscopic and open radical prostatectomy. Robotic and laparoscopic techniques are minimally invasive procedures with similar patient benefits, but the newer robotic technique requires a high initial investment cost to purchase the robot and carries high maintenance costs over time. Using data from a large UK administrative database, Hospital Episodes Statistics, for the period 2000–2018, we analyse 173 hospitals performing radical prostatectomy, the most prevalent and earliest surgical area of adoption of robotic surgery. Our empirical analysis first identifies substitution effects, with robotic surgery replacing the incumbent technology, including the recently diffused laparoscopic technology. We then quantify the spillover of robotic surgery as it diffuses to other surgical specialties. Finally, we perform time-to-event analysis at the hospital level to quantitatively examine the adoption. Results show that a higher number of urologists and a wealthier referral area favor robot adoption.

1. Introduction

Technology adoption in health care, generally motivated by the potential to achieve improvements in health outcomes [1], has also been identified as a major driver of health care expenditure for most developed countries [2–4]. While there is a vast literature on the cost-effectiveness surrounding the introduction of individual technologies, there is less attention paid to the determinants of adoption and diffusion of technology in the health sector. Analysis of the adoption and diffusion of new technologies in the health care sector is largely confined to describing the patterns of adoption. Some studies do go further to analyse the process of substitution for incumbent technologies [5–8] or to document the quality improvement of the new technology as it replaces the old one [6,9]. Different lines of research have also focused on different technology types, such as drug diffusion [10–12], physical capital [13–15], health technology information [16, 17] or surgical procedures [18–20].

In this paper we focus on the adoption and diffusion of robotic surgery in the context of the English National Health Service (NHS). This is of interest as robotic surgery is increasing rapidly, often with little supporting clinical or cost-effectiveness evidence, and comes with higher capital and perioperative costs. The cost of purchasing a robot is roughly £1.7 m and comes with high running costs (£1000/patient for disposables and £140,000/year for maintenance [21]). Generally, the determinants of new technology adoption remain largely unexplained. While adoption is changing rapidly, the most common use of robotic surgery within many health care systems, and certainly within the NHS, remains associated with urology generally and radical prostatectomy specifically. Radical prostatectomy is defined as the removal of the prostate gland and attached seminal vesicles, which is usually performed to treat cancer [22].

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The first surgical procedure available to treat radical prostatectomy was open surgery, followed by laparoscopic and most recently robotic surgery. Laparoscopic and robotic surgery are minimally invasive techniques and were introduced as alternative surgical techniques to open procedures, given their improved clinical outcomes. The spread of robotic surgery within the NHS has been extremely swift, after a relatively slow start, over the past decade. The first da Vinci robot, the earliest form of surgical robot, was classed as a medical device and only required clearance from the Medicines and Healthcare products Regulatory Agency (MHRA) in regards to its safety and its specific purpose. It was first introduced into the NHS at St Mary's NHS Hospital in 2000, followed by Guy's & St Thomas' NHS Foundation Trust in 2004. After that, as we show below, there was a rapid adoption of robots within NHS England. The proportion of robotic surgery used for radical prostatectomy increased from 5% in 2006 to 88% of all prostatectomies performed within the English NHS in 2018.

The flexibility and versatility of robotic surgery coupled with its greater precision hold promise of more effective patient outcomes across a number of hospital specialties. However, existing evidence suggests that robotic surgery for prostatectomy does not generally appear to be more clinically effective than laparoscopic [23–27]. The comparison between robotic and laparoscopic prostatectomy indicates that patients undergoing robotic surgery report a slightly better sexual function but there are no differences in urinary incontinence, urinary irritation, bowel and hormonal function or quality of life [25]. Also, the little evidence that exists on the impact of using the robotic technique, compared to the alternative minimally invasive technique of using laparoscopic surgery, on length of stay, 30-day readmission and follow-up visits indicates no clear gains to the adoption of a robot for treatment [28].

The focus on the NHS is of interest for a number of additional reasons. First, the NHS accounts for just under 90% of total health care expenditure nationally. Second, NHS hospitals' generally manage their own affairs and have discretion over their expenditure. In order to purchase the new and costly robotic technology, NHS hospitals' had to put together a business-case which has to be approved by the hospital's Board of Directors and agreed with the relevant Clinical Commissioning Group (CCG, former Primary Care Trust (PCT)) who act as the purchasers of healthcare on behalf of geographically determined populations [29]. In other countries procurement decisions in regards to costly new technology are taken by regulatory bodies centrally. For instance, in the US, purchase of medical equipment are controlled under Certificates of Need regulations, although such regulations are open to State level interpretation [30]. In contrast, hospital providers in the English NHS have considerable autonomy in adopting this type of new equipment.

Despite the lack of a unified framework for NHS procurement, hospitals are subject to centralised guidance over new treatments and procedures. There was a significant lag between the first introduction of the robot in 2000 and 2014 when the National Institute for Health and Care Excellence (NICE), the agency that provides supportive evidence for the adoption of new technologies into the NHS, published clinical guidelines for the robotic treatment and management of prostate cancer. NICE advised robotic surgery should only be based in high volume centres with at least 150 robot-assisted laparoscopic radical prostatectomies per year [31]. Updated guidelines confirmed the same recommendations [32]. Nonetheless robotic surgery diffused rapidly in England, including in centres where volumes did not reach the recommended NICE volume threshold. The guidelines were indicative of minimum volumes needed for robotic use to be cost-effective and the recommendation was non-binding. NHS providers were not required to meet the threshold to adopt the technology.

Based on this background, the aim of this paper is threefold: (1) to provide a full description of the sequential adoption and diffusion patterns of robotic surgery within the English NHS, documenting the recent rapid diffusion of robotic prostatectomy as it substitutes for both laparoscopic and open prostatectomy; (2) to examine the increasing use of robotic surgery in other surgical areas, in what we call surgery spillover; and (3) to identify the key factors determining the adoption of robotic surgery for radical prostatectomy using time-to-event models.

While previous research has descriptively outlined the use of robotic surgery in England particularly in the treatment of radical prostatectomy [33,34], there has been little empirical analysis of the determinants of robotic surgery adoption and diffusion. To the best of our knowledge, this is the first study to perform a time-to-event analysis to examine the determinants of adoption and diffusion of robotic surgery across a healthcare system. By using information on both the decision to use the robotic intervention and the timing of that decision we can fully assess the diffusion of this new technology as it replaces both laparoscopic and open surgery. Our analysis examines the diffusion process at the hospital level, as opposed to the strand of literature that focuses on the motivational factors and peer networks of individual surgeons to adopt the robotic surgical technique [35–38]. Both approaches complement each other and contribute to the better understanding of robotic diffusion.

The paper is structured as follows. In Section 2 we describe our data and the evolution of the three competing technologies in England. We follow this by outlining the empirical strategy used to investigate robotic surgery diffusion, the spillover of robotic surgery to other surgical specialties and the factors determining adoption. Section 3 presents the results of our analysis. Section 4 discusses the results and the last section concludes.

2. Methods

2.1. Data

To empirically examine the adoption of the robotic surgery for radical prostatectomy, we use the NHS Hospital Episode Statistics (HES), a rich administrative dataset which includes all episodes for patients admitted into hospitals in England. Each patient record contains clinical information on admission date, diagnosis, main operation, date of operation, anonymised consultant code, discharge date, patient-mix characteristics and several organisational variables. We use all records from financial year 2000/2001 to 2018/19 for each patient admitted into hospital for open, laparoscopic or robotic prostatectomy based on surgical procedure codes (OPCS-4) for the main operation.

We construct a longitudinal dataset that includes total volumes for the three radical prostatectomy procedures by provider and year. The final dataset is an unbalanced panel of 173 hospital providers from 2000 to 2018 that perform radical prostatectomy. From these hospital providers, 90 only perform open prostatectomy, while 30 perform both open and laparoscopic, and another 53 perform all three interventions. To examine the surgical spillover of robotic surgery from urology into other surgical specialties, we extract from HES the volume of robotic procedures in other specialties per provider and year, using OPCS-4 procedure codes once again.

We construct provider-averaged information on patient casemix from the individual patient records, such as patient age, Charlson Comorbidity Index and Index of Multiple Deprivation (income domain - IMDI) of the area where the patient resides. Additionally, we include provider characteristics to reflect on foundation trust status, teaching hospital status, average bed occupancy rate at the aggregated hospital level (as a measure of capacity), total number of sites which the hospital occupies for health care service delivery and total annual admissions. Foundation trust status is defined as a semi-autonomous organisational unit within the NHS. These trusts were created, under governmental license, to devolve decision making from central government to local organisations, enabling them to be responsive to local population needs. Compared to normal NHS hospital trusts, they have some managerial and financial freedom, being allowed to rollover financial surpluses and decide upon specific treatments (although the latter still have to meet the regulatory requirements of the NHS). This variable identifies the degree of management autonomy the hospital holds.

We calculate the number of consultant urologists per provider and the year during which the hospital performs robotic, laparoscopic or open radical prostatectomy. We also include the percentage of male population aged 55 years and over by PCT, to identify the at-risk population. These control variables are used as explanatory variables as a means of standardizing referral patterns to control for possible selection bias and are consistent with previous research on barriers to entry associated with minimal access surgeries [36].

2.2. Empirical strategy

We undertake three sets of complementary empirical analyses. First, we consider diffusion in terms of the degree of substitution or complementarity across the three technologies over nearly two decades. While robotic surgery is used predominately for prostatectomy, we then empirically examine the spillover of robotic surgery into other surgical specialties. Finally, we perform a time-to-event study using a flexible parametric model including a range of covariates to help explain robotic surgery adoption. The equations for these models are presented in the Appendix - Extension Empirical Strategy.

2.2.1. Longitudinal analysis of technology diffusion

Robotic surgery diffusion is examined at the provider level by quantifying the elasticity of substitution or complementarity between the three technologies. We specify diffusion models drawing on related specifications used previously by Cutler and Huckman [19] and McGuire et al. [20].

Our first specification covers the whole study period 2000 to 2018, examining the substitution or complementarity effects of the minimally invasive techniques, robotic and laparoscopic, compared to open surgeries. Next, we delimit the analysis to the period 2000–2006 to focus on the interaction of the incumbent technology, open surgery, with the competing laparoscopic prostatectomy, which was the first minimally invasive procedure introduced. We finally explore the interaction between the two minimally invasive procedures, laparoscopic and robotic surgery, in order to quantify the level of substitution between these two medical technologies. Although laparoscopic surgery for radical prostatectomy was available from early 2000s, we restrict our sample to the period 2006 to 2018, when both minimally invasive techniques were available.

The dependent and the main variables of interest measure technology volume by provider i at year t adjusted by male population at risk (aged 55 and above). The coefficient of interest is β_1 with negative (positive) signs representing substitution (complementarity). All specifications include a set of control variables X_{it} (patient and hospital characteristics) as defined in the data section. We include hospital fixed-effects c_i to capture unobserved hospital heterogeneity and year-fixed effects T_t to account for any sectoral specific reforms that might impact on technology adoption. The fixed effects approach is our preferred specification as it deals with remaining hospital level unobserved heterogeneity, and is further supported as random effects specifications were generally not accepted by the Hausman test.

2.2.2. Longitudinal analysis of surgical spillover

We also examine the potential surgical spillover of robotic surgery from the initial specialty of use, urology, into other surgical specialties. The main hypothesis is that once a hospital invests in a robot for radical prostatectomy, the robotic technique may spill over to other surgical specialties to maximize the investment of purchasing such technology.

The model tests whether there is an expansion of robotic-assisted prostatectomy and surgery in other specialties that also use the robot. The dependent variable covers all procedures other than radical prostatectomy performed with the robot. We then break other robotic procedures down into the two most common robotic surgeries other than radical prostatectomy, namely obstetrics and abdominal surgery. In all cases a positive β_1 represents expansion.

2.2.3. Time-to-event analysis

We define the three following events (failures) of interest: (1) delay in adoption, that is, time from first hospital in the dataset using robotic surgery for radical prostatectomy to other hospitals taking up use of a robot for radical prostatectomy; (2) time to achieving a minimum of 150 robotic surgical volumes in radical prostatectomy as defined by the NICE guidelines [31,32]; (3) time from performing robotic prostatectomy in any given hospital to that of performing robotic surgery to other specialties (spillover). All these events have censored observations given not all hospitals adopt a robot in our first analysis, meet the threshold of a minimum 150 robotic surgical interventions, or expand the use of the robot to other specialties. For each event, we use a flexible time-to-event parametric survival model [39].

3. Results

3.1. Descriptive statistics

Fig. 1(I) shows the population-adjusted volumes for radical prostatectomy from 2000/01 to 2018/19. Open prostatectomy appears to be substituted by laparoscopic, but robotic prostatectomy then rapidly substitutes both open and laparoscopic surgery. Our data shows that while the average annual rate of growth was −5.06% for open prostatectomy and 22.95% for laparoscopic during the period 2000–2018, it was 40.34% for robotic during the period of 2006–2018. On aggregate just over half of the providers (29 out of 53 hospitals) achieve the minimum 150 volume of robotic surgery per year recommended by NICE. The geographical adoption of robotic surgery by NHS England providers has changed over time, as shown by Fig. A1 in the Appendix. All hospitals perform open prostatectomy, 83 hospitals perform laparoscopic prostatectomy and 53 of them use robotic-assisted techniques. The maps show the rapid geographical adoption of robotic surgery, with the majority of providers already performing laparoscopic interventions before adopting robotic surgery.

Fig. 1(II) shows the potential surgical spillover that accompanies the introduction of robotic-assisted prostatectomy. The upward trend in total prostatectomy volume is in line with an increase in the incidence of prostate cancer [40]. As this technology becomes widely used, the robotic technique is implemented in other surgical specialties such as abdominal (i.e., rectal and colon, kidney, lungs, bladder, endoscopic prostatectomy, gall bladder and coronary arteries) and obstetrics procedures (i.e., vaginal and uterine interventions). Fig. 1(III) shows the breakdown of all robotic surgeries other than prostatectomy. There are a small number of hospitals that initially introduce the robot for other surgical specialties, for which volumes stay extremely small until the robot is introduced for performing prostatectomy.

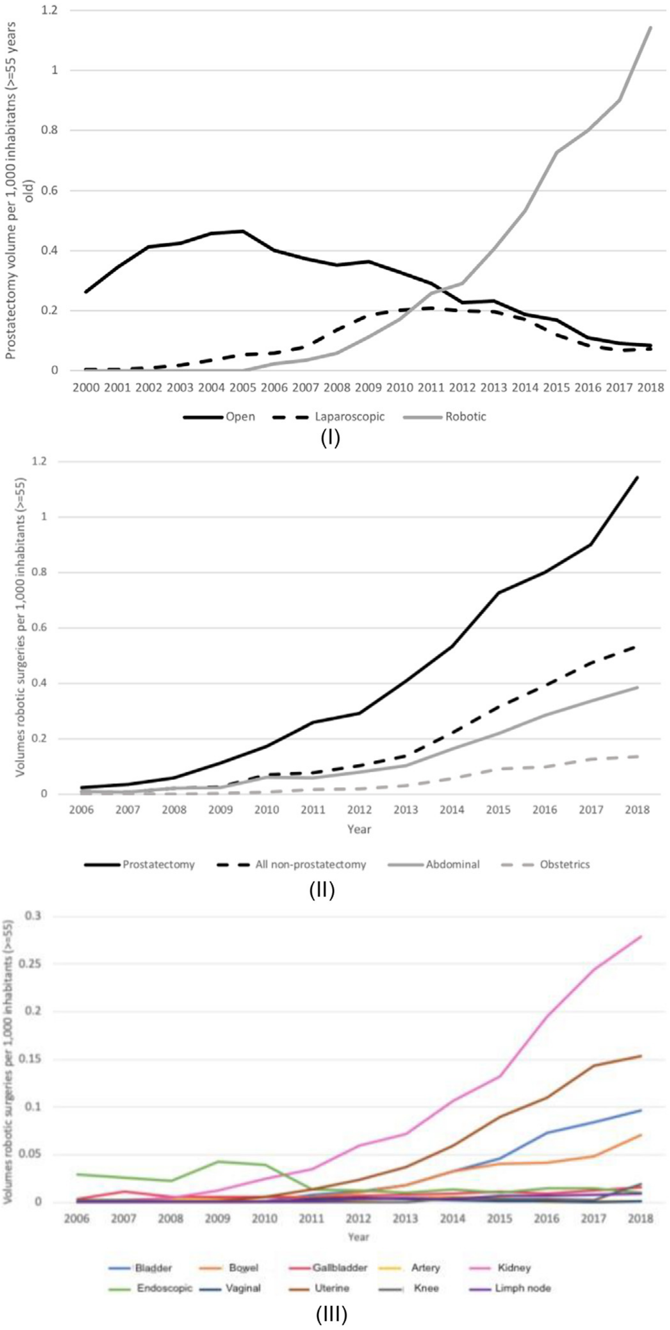

Fig. 1. Robotic Volumes. (I)- Radical Prostatectomy volumes. (II)- Robotic surgery volumes disaggregated. (III)- Robotic surgery volumes by surgical specialty (excludes prostatectomy).
Source: HES data.

Table A1 lists the variables used in the analysis and provides descriptive statistics at the hospital level over the whole of the study period. The average prostatectomy volumes per provider and year were 21.3 for open, 7.7 for laparoscopic and 23 for robotic. For all other robotic surgeries, the average was 10.1 per provider and year. The average patient was 63 years-old and a Charlson Comorbidity Index of 2.2. In the sample, 31% of the providers were foundation trusts and 29% were teaching trust. These providers had an average occupancy rate of 86%, 1.5 sites and 2.6 urologists. About 54% of hospitals performed the three competing interventions.

Table A2 in the Appendix highlights the characteristics of hospitals meeting the threshold for cost-effectiveness of 150+ robotic prostatectomies first recommended by NICE in 2014, compared to those not reaching this threshold in 2014. These are mostly teaching hospitals, hospitals with foundation trust status, larger hospitals and hospitals with greater numbers of urologists. In adopting a robot, hospitals consider an internal business-case with evidence on volume and technology costs [29]. Our data indicates that a proportion of hospitals acquired a robot even though they did not meet the volume threshold suggested by NICE. NICE publishes the treatment guidelines but these are not binding. Hence, hospitals could adopt the robot with other considerations in mind, ignoring NICE recommendations rather than expecting to meet the volumes associated with the cost-effective guidance.

3.2. Longitudinal analysis of technology diffusion

Table 1 shows the estimates of a fixed-effects panel data model reporting the degree of substitution/complementarity between our three technologies at the provider and year level. The dependent variable is the volume of open prostatectomy in Columns (1) to (4), and the volume of laparoscopic prostatectomies in Column (5). The main explanatory variable is the corresponding measure for robotic and/or laparoscopic prostatectomy volumes.

Columns (1) to (3) estimate the model for the full period. In column (1), the estimates are obtained using the whole sample which includes all providers (including those that only perform open procedures), and suggest there exist substitution between minimally invasive surgery and open. In Column (2) we restrict the sample to those providers that do robotic and lap only and those that do the three surgical techniques. Column (3) shows the estimates when we further restrict the sample to providers that do all three techniques and the results are in line to those in Columns (1) and (2). On average, an additional laparoscopic or robotic intervention per 1000 inhabitants, decreases open by 0.2 and 0.1 interventions per 1000 inhabitants, respectively. Given the negative and statistically significant signs on all the relevant variables there is evidence of strong substitutability for both laparoscopic and robotic interventions with respect to open prostatectomy.

Column (4) shows the results when restricting the sample to the 2000–2006 period to examine the relationship between open and laparoscopic. The negative and statistically significant estimate indicates there is an extremely strong substitution effect between the two older technologies. An increase of 1 laparoscopic intervention per 1000 inhabitants, decreases open by 0.5 interventions per 1000 inhabitants. Column (5) shows the results of estimating the period after the introduction of robotic prostatectomy, suggesting a substitution effect of the robotic technique for the laparoscopic. An increase of 1 robotic intervention per 1000 inhabitants, decreases laparoscopic by 0.09 interventions per 1000 inhabitants. Columns (4) and (5) show how technological change occurs over time. Firstly, laparoscopic procedures strongly replace open (during the 2000–2006 period) and secondly, robotic procedures somewhat more weakly replace laparoscopic (from 2006 onwards).

Table 2, column (1) to (3), reports the estimated coefficients of all control variables (capturing patient case-mix and hospital characteristics) corresponding to the specifications in columns (1), (4) and (5) in Table 1 (results are available for all specifications in Table A3 in the Appendix). Most of the explanatory variables are not statistically significant, except for the number of total admissions and the number of urologists which both increase the number of open prostatectomy procedures.

To gain a better understanding of differences in the substitution effect across hospital types, we estimate the coefficients according to hospital teaching status. Table 2 presents the estimates for teaching and non-teaching hospitals (Tables A4 and A5 in the Appendix show the results for all corresponding specifications

Table 1
Technology diffusion.

Dep. Variables	(1) Open	(2) Open	(3) Open	(4) Open	(5) Laparoscopic
Laparoscopic	−0.197***	−0.206***	−0.163***	−0.515***	
	(0.053)	(0.054)	(0.068)	(0.156)	
Robotic	−0.100***	−0.102***	−0.093***		−0.089*
	(0.032)	(0.033)	(0.040)		(0.052)
No. Hospitals	136	81	53	79	53
N	1575	1242	613	498	613
Time fixed-effects	Yes	Yes	Yes	Yes	Yes
Providers fixed-effects	Yes	Yes	Yes	Yes	Yes
Sample: hospitals	all	open+lap/all 3	all 3	open+lap/all 3	all 3
Controls Patients	Yes	Yes	Yes	Yes	Yes
Controls Providers	Yes	Yes	Yes	Yes	Yes
R^2	0.328	0.349	0.429	0.285	0.208
Years	2000–2018	2000–2018	2000–2018	2000–2006	2006–2018

Notes: The variables on technology volumes (open, laparoscopic and robotic) are adjusted over the male population aged 55 and above (in 1000s). Control variables: Charlson Comorbidity Index, Index of Multiple Deprivation (Income) of the area where the patient resides, mean age, percentage of population over 55 by PCT, bed occupancy rate per hospital, total number of admissions per hospital, total number of sites per hospital, number of urologist and foundation trust dummy. Robust standard errors in parentheses. Significance levels: ***$p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 2
Technology diffusion by hospital type.

Sample Dep. Var.	(1) Full Open	(2) Teaching Open	(3) Non-Teaching Open	(4) Full Open	(5) Teaching Open	(6) Non-Teaching Open	(7) Full Lap.	(8) Teaching Lap.	(9) Non-Teaching Lap.
Laparoscopic	−0.197***	−0.182**	−0.244**	−0.515***	−0.484*	−0.607***			
	(0.053)	(0.075)	(0.098)	(0.156)	(0.237)	(0.191)			
Robotic	−0.100***	−0.083**	−0.150**				−0.089*	−0.049	−0.223***
	(0.032)	(0.036)	(0.074)				(0.052)	(0.044)	(0.039)
Foundation Trust (=1)	0.030	0.104	−0.013	0.036	0.008	0.029	0.194	0.613	−0.038
	(0.075)	(0.145)	(0.091)	(0.070)	(0.159)	(0.068)	(0.246)	(0.369)	(0.244)
Av. IMDI	−0.612	−2.537**	0.256	−1.280	−3.131*	0.331	0.195	5.971*	−4.061
	(0.457)	(1.055)	(0.455)	(0.853)	(1.636)	(0.747)	(1.779)	(3.283)	(2.617)
Av. CCI	0.037	−0.080	0.080***	−0.069	−0.322*	0.012	−0.126	−0.241	0.259
	(0.026)	(0.064)	(0.030)	(0.083)	(0.165)	(0.082)	(0.205)	(0.442)	(0.304)
Av. Age	−0.001	0.001	−0.008*	0.007	0.013*	−0.005	0.001	0.011	−0.014
	(0.003)	(0.006)	(0.004)	(0.005)	(0.007)	(0.007)	(0.016)	(0.033)	(0.024)
Occupancy rate	−0.002	0.011	−0.005	−0.004	−0.016	−0.001	−0.007	−0.019	0.014
	(0.005)	(0.010)	(0.004)	(0.005)	(0.012)	(0.004)	(0.009)	(0.014)	(0.011)
Log number of sites	−0.005	0.014	−0.021	0.039	0.078	0.038	−0.028	−0.073	0.005
	(0.021)	(0.034)	(0.025)	(0.037)	(0.121)	(0.029)	(0.032)	(0.049)	(0.048)
Prop. population 55+	−0.042	−0.062	−0.029	−0.127***	−0.109*	−0.139**	−0.025	−0.021	−0.037
	(0.035)	(0.058)	(0.046)	(0.037)	(0.059)	(0.057)	(0.146)	(0.312)	(0.089)
Number of admissions	0.001***	0.001	0.001***	0.001*	0.003	0.001*	−2.21e-05	−0.0003	0.0001
	(0.0002)	(0.0003)	(0.0002)	(0.001)	(0.002)	(0.0004)	(0.0002)	(0.0003)	(0.0001)
Urology consultants	0.110***	0.142**	0.091***	0.114***	0.128***	0.110***	0.047	0.057	0.071**
	(0.026)	(0.052)	(0.018)	(0.020)	(0.035)	(0.027)	(0.038)	(0.065)	(0.029)
No. Hospitals	136	32	104	79	26	53	53	23	30
N	1575	466	1109	498	162	336	613	265	348
Time fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Provider fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sample: hospitals	all	all	all	open+lap/ all 3	open+lap/ all 3	open+lap/ all 3	all 3	all 3	all 3
Controls Patients	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls Providers	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.328	0.347	0.379	0.285	0.342	0.341	0.208	0.248	0.334
Years	2000–2018	2000–2018	2000–2018	2000–2006	2000–2006	2000–2006	2006–2018	2006–2018	2006–2018

Notes: The variables on technology volumes (open, laparoscopic and robotic) are adjusted over the male population aged 55 and above (in 1000s). Robust standard errors in parentheses. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. IMDI: Index of Multiple Deprivation (Income). CCI: Charlson Comorbidity Index.

from Table 1). Results by hospital type follow the same pattern of the full sample, but the substitution effect is higher in the non-teaching hospitals. This could potentially be explained by teaching hospitals being earlier adopters, and a more gradual substitution effect thereafter as a consequence. In contrast, non-teaching hospitals make use of the new intervention quicker as soon as the technology is adopted, although adoption is later. The effect of the control variables in these specifications are in line with the results obtained for the full sample, with the only difference being that models in columns (4) to (6) the population over 55 decreases volume.

3.3. Longitudinal analysis of surgical spillover

Table 3 presents the results of the up-take of robotic prostatectomy volumes as it diffuses the use of robotic surgery to other specialties. We first consider whether other surgical procedures were performed using robotic surgeries, once a robot had been used to

Table 3
Robotic surgery spillover.

Dep. Variables	(1) Robotic Other	(2) Robotic Obstetric	(3) Robotic Abdominal
Robotic Prostatectomy	0.215*	0.060	0.146**
	(0.110)	(0.060)	(0.055)
No. Hospitals	53	53	53
N	613	613	613
Sample: Hospitals	open+lap+rob	open+lap+rob	open+lap+rob Time fixed-effects
Time fixed-effects	Yes	Yes	Yes
Provider fixed-effects	Yes	Yes	Yes
Controls Patients	Yes	Yes	Yes
Controls Providers	Yes	Yes	Yes
R^2	0.521	0.242	0.486
Years	2006–2018	2006–2018	2006–2018

Notes: See notes in Table 1. Robust standard errors in parentheses. Significance levels: *** $p < 0.01$. ** $p < 0.05$, * $p < 0.1$.

treat prostatectomy (Column (1)). The positive coefficient suggests there is a diffusion (spillover) effect. The introduction of the robot for prostatectomy does indeed lead to the spread of robotic surgery to other specialties. Our data shows the robot is used mainly for two surgical specialties other than urology, obstetrics and abdominal interventions. Results are shown in Columns (2) and (3), respectively. Again, the positive estimates indicate an expansion effect, but it is only statistically significant for abdominal surgery. The overall effect is an output expansion effect into additional surgical specialties, mainly driven through the use of the robot for abdominal surgeries.

Furthermore, in our disaggregated model of robotic spillover groups (abdominal and obstetrics), we see the highest rates of diffusion among abdominal surgery was in partial nephrectomy (see Fig. 1(III)), with lower rates of diffusion in more general obstetrics surgery which is consistent with the clinical literature [34].

3.4. Time-to-event analysis

Table 4 presents the results of the time-to-event analysis in order to identify the potential predictors of robotic surgery adoption, diffusion and spillover of robotic use into other surgical specialties. Column (1) reports the estimates when using the definition of time to event based on the time from first robot ever adopted across the NHS to the time a hospital adopts a robot. Results show that having a greater number of urologists within the hospital and being in a wealthier catchment area favor the adoption of robotic surgery for radical prostatectomy.

Column (2) of Table 4 reports results when using time to the point where a provider reaches the NICE threshold of 150+ robotic prostatectomy interventions per year from the time of initial adoption within that (given) hospital provider. The sample is restricted to the 53 hospitals performing robotic surgery. Of these 53, only 29 reached this minimum regulatory number of interventions throughout the period. Being a foundation trust, a teaching trust and having an extra urologist increased the probability of reaching the threshold set by NICE. However, our data indicates that a higher occupancy rate decreased the probability of reaching the minimum 150 surgical interventions per year. A plausible explanation is that higher occupancy rates (and therefore less bed availability) could constrain the number of interventions, hindering a hospital's ability to reach the minimum 150 interventions per year.

Column (3) of Table 4 outlines the results relating to the time from first robotic prostatectomy in a hospital to the time of first robotic surgery in another surgical specialty within that hospital. We do not disaggregate the different specialties, but rather keep them grouped together for simplicity. Out of 53 hospitals with a robot, 25 used the robot for prostatectomy first. The remaining 28 hospitals undertook robotic surgery in another specialty first but the volumes of robotic use were extremely small, with hospitals delaying the expansion into larger robotic volumes until after the hospital has begun undertaking robotic prostatectomy. Column (3) therefore reports the results for the 25 hospitals that start robotic surgery with prostatectomy, showing that higher admissions, having an extra urologist and a younger population are all significant predictors of the spillover effect of robotic surgery into other surgical specialties. However, being a foundation trust is negatively associated with time to roll-out to another surgical areas.

To examine more in detail the relationship between the number of urologists and a hospital adopting a robot, we looked in the data at the absolute number of urologists in hospitals which had a robot and those which did not. The average number of urologists in hospitals with a robot was 3.52 urologists (for the year the robot was bought), while the average number of urologists in those without a robot was 1.26 urologists. Hospitals with a robot have on average two additional urologists compared to those trusts without, and the difference is statistically significant. This is a large proportion given the average number of urologists in any given hospital (those with and without a robot) is 2.15. Hence, the more urology consultants a hospital has, the more likely the hospital is to adopt a robot.

4. Discussion

The aim of this paper was to examine the rapid adoption and diffusion of robotic surgery within the NHS in the area of radical prostatectomy. Robotic surgery in the NHS for radical prostatectomy has experienced an unprecedented surge, compared to other minimally invasive techniques, and rapidly replaced incumbent technologies becoming the most common surgical procedure for prostatectomy. However, clinical evidence suggests that robotic surgery brings marginal gains in clinical outcomes compared to laparoscopic surgery, unlikely to offset its cost.

Understanding the adoption and diffusion of this type of technology is important from the policy perspective given that medical technologies are large contributors to the growth in national health care expenditures, not only through a substitution effect but also adding technology use via an expansion effect [19,20]. In this paper we first examine the interaction between incumbent and newer technologies, to determine whether they are substitutes for existing technologies and quantify the magnitude of the effect. Secondly, we then quantify robotic diffusion through its potential spillover into other surgical specialties. Thirdly, we used time-to-

Table 4
Time-to-event analysis (hazard ratios).

Dep Variables	(1) Robot Use	(2) NICE 150+ threshold	(3) Spillover to other specialties
Laparoscopic (=1 Yes)	4.513e+08		
	(6.726e+11)		
Foundation Trust (=1 Yes)	0.894	2.203*	0.254**
	(0.295)	(0.949)	(0.167)
Teaching Trust (=1 Yes)	1.523	2.141*	0.702
	(0.518)	(0.953)	(0.454)
Occupancy rate	0.965	0.939*	1.118
	(0.024)	(0.035)	(0.077)
Log number of sites	0.878	1.080	0.778
	(0.125)	(0.233)	(0.211)
Number of Admissions	1.000	0.999	1.002***
	(0.0004)	(0.001)	(0.001)
Urologist consultants	1.522***	1.246*	1.549**
	(0.138)	(0.163)	(0.265)
Prop. population 55+	0.954	1.064	0.932
	(0.038)	(0.047)	(0.066)
Av. IMDI	0.004*	0.096	1.30e-05
	(0.011)	(0.618)	(0.0001)
Av. CCI	0.210	2.344	37.97
	(0.226)	(5.202)	(119.2)
Av. Age	0.925	1.160	0.738*
	(0.048)	(0.160)	(0.136)
No. of Hospitals	123	53	25
N	123	53	25
Sample: Hospitals	all	open+lap+rob	open+lap+rob
Controls Patients	Yes	Yes	Yes
Controls Providers	Yes	Yes	Yes
Years	2006–2018	2006–2018	2006–2018

Notes: We use data from 2006 as there are missing values in some covariates and the sample accounts for all 123 hospitals.

In Column (3) the competing specialties in the non-prostatectomy group are: abdominal (i.e. rectal and colon, kidney, lungs, bladder, gall bladder and coronary arteries) and obstetrics procedures (i.e., vaginal and uterine interventions). Robust standard errors in parentheses. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. IMDI: Index of Multiple Deprivation (Income). CCI: Charlson Comorbidity Index.

event analysis to identify the key factors determining the adoption and diffusion of robotic surgery within the English NHS.

Our results suggest a strong substitution effect across the technologies and documented a rolling-out of technology replacement. First, laparoscopic procedures replaced open (2000 to 2006), then robotic procedures rapidly replace laparoscopic surgery (2006 onwards) for the treatment of prostate cancer. From 2006 to 2018 robotic prostatectomy was introduced into the English NHS and quickly gained popularity. We were particularly interested in this diffusion phase of robotic technology, given the significantly higher costs of provision to a population that had already seen significant improvements associated with the uptake of laparoscopic procedures.

Our results also confirm expansion of the use of robotic surgery in other surgical procedures through surgical treatment spillover. This effect is mainly observed through the expansion of robotic-assisted surgery in abdominal surgeries, once robotic surgery is introduced for radical prostatectomy. A potential mechanism to explain this phenomenon is that surgeons gain knowledge on the performance of robotic prostatectomy over time and within any given hospital there are surgical spillover effects from initial adopters to other surgeons. These results are in line with the small previous literature that has considered this effect [41]. Our further disaggregation of surgical groups into more specific surgery types revealed partial nephrectomies to have the next highest rate of diffusion after radical prostatectomies, while the obstetric group revealed a slower rate of up-take. Again, these results are in line with previously reported clinical studies [34].

Although robotic surgery has been predominantly used for prostatectomy in England, its expansion to other surgical specialties could help reduce average costs. During our study period, the only robot available in the NHS was the da Vinci robot, but new robots are currently under development as several patents of the da Vinci robot have expired recently. The expected cost of new robots is set to be lower but there remains the question of whether they will bring any additional improvements in health outcomes.

The analysis nonetheless shows there was low adherence to regulatory guidelines, as only 55% of hospitals performing robotic surgery reached cost-effective levels of production as defined by NICE recommendations. A large proportion of these hospitals were teaching hospitals, had foundation trust status, higher number of urologists and bigger hospitals. More urologists in larger hospitals may form networks of peers that facilitate meeting NICE recommendations but also encourage the expansion of robotic to other surgical areas, training peers in the use of robotic surgery and explaining the high uptake of this technique into abdominal surgery.

The time-to-event analysis identified some of the key factors determining robotic adoption. Across the three events examined, results show consistently that the main mechanism of robotic surgery adoption is the number of urologist(s) in the hospital, with an average of 2 extra urologist in hospitals with robotic surgery. This finding supports the argument that greater bargaining power, as reflected by higher number of urologists in a hospital, leads to a greater probability of a hospital adopting a robot.

Having an extra urologist and being in wealthier referral area favor the adoption of robotic surgery for radical prostatectomy.

While being a teaching and foundation trust increase the probability of reaching the minimum level of 150 robotic interventions per year. Lastly, being a foundation trust hospital and larger providers were the main predictors of subsequently using the robot in other surgical specialties.

5. Conclusion

The rapid adoption and diffusion of robotic surgery in radical prostatectomy has substituted for earlier laparoscopic and open technologies. The adoption of robotic surgery appears to be a prime example of the rapid diffusion of a new technology prior to effectiveness having been clearly established in any given area. This lack of evidence on effectiveness is clearly not a UK specific matter, and we postulate that the rapid diffusion of robotic surgery in other surgical specialties is also related to promise rather than fact. Of course, gathering such evidence is difficult as surgery involves a volume-outcome relationship, and the learning of new skills with new procedures. However, without clear clinical advantage the new technology remains under development. It may be, especially given that UK teaching hospitals and foundation trusts hospitals with their more liberal management practices appear to be early adopters, that the new technology signals quality and cutting-edge development but this comes at a cost. The adoption of robotic surgery relies on initial pressure from surgeons within a specific surgical specialty, which then promotes diffusion to other surgical procedures. Our findings highlight the need for even greater understanding of how this technology has rapidly come to dominate a particular surgical area and is rapidly rolling out to others.

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Availability of data and material

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Conflicts of interest

There are no conflicts of interest for any of the authors. All authors freely disclose any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations that could inappropriately influence, or be perceived to influence, their work.

CRediT authorship contribution statement

Laia Maynou: Conceptualization, Methodology, Formal analysis, Visualization, Writing – review & editing, Validation. **Georgia Pearson:** Data curation, Formal analysis, Visualization, Writing – original draft. **Alistair McGuire:** Supervision, Conceptualization, Methodology, Validation, Writing – review & editing. **Victoria Serra-Sastre:** Supervision, Conceptualization, Methodology, Validation, Writing – review & editing.

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Appendix

Extension empirical strategy

This section provides the equations defined in the empirical strategy.

1. Longitudinal analysis of technology diffusion. To establish a relationship between the procedures, we draw on Cutler and Huckman [19] and McGuire et al. [20] and use the related empirical specifications:
    - 2000–2018:

$$\frac{Open\_prost}{pop55}_{it} = \alpha + \beta_1 \frac{Lap\_prost}{pop55}_{it} + \beta_2 \frac{Rob\_prost}{pop55}_{it} + \gamma\prime X_{it} + T_t + c_i + u_{it} \tag{1}$$

    - 2000–2006:

$$\frac{Open\_prost}{pop55}_{it} = \alpha + \beta_1 \frac{Lap\_prost}{pop55}_{it} + \gamma\prime X_{it} + T_t + c_i + u_{it} \tag{2}$$

    - 2006–2018:

$$\frac{Lap\_prost}{pop55}_{it} = \alpha + \beta_1 \frac{Rob\_prost}{pop55}_{it} + \gamma\prime X_{it} + T_t + c_i + u_{it} \tag{3}$$

    The dependent and the main variables of interest measure technology volume by provider i at year t adjusted by male population at risk (aged 55 and above). The coefficient of interest is β_1 with negative (positive) signs representing substitution (complementarity). All specifications include a set of control variables X_{it} (patient and hospital characteristics) as defined in the data section. We include hospital fixed effects c_i to capture unobserved hospital heterogeneity and year-fixed effects T_t to account for any sectoral specific reforms that might impact on technology adoption. Finally, u_{it} is the disturbance term.

2. Longitudinal analysis of surgical spillover:

$$\frac{Other\_rob}{pop55}_{it} = \alpha + \beta_1 \frac{Rob\_prost}{pop55}_{it} + \gamma\prime X_{it} + T_t + c_i + u_{it} \tag{4}$$

3. Time-to-event analysis

$$ln[H(t)|x_i] = s(ln(t)|\gamma, k_0) + \beta X_i \tag{5}$$

Eq. (5) presents a log cumulative hazard scale, with a restricted cubic spline (rcs) function of ln(t), with knots, k_0, that can be written as $s(ln(t)|\gamma,k_0)$. The model follows a log cumulative hazard scale, with a restricted cubic spline (rcs) function of ln(t), with knots. The splines allow substantial flexibility of fit to the data and the models also allow us to account for a set of covariates (X_i) that are potential predictors of the event. This model, originally proposed as an alternative to the Cox model which imposes proportional hazards, allows flexibility in specification choice as it permits absolute measures of continuous failure time across a range of complex functional forms. The basic idea of the flexible parametric approach is to relax the assumption of linearity of log time by using restricted cubic splines [42].

Table A1
Descriptive Statistics.

Variable	Definition	Source	N	Mean	St.Dev	Min	Max
v_prost	Open Prostatectomy volume	HES	1709	21.26	23.02	0	235
v_lapprost	Laparoscopic Prostatectomy volume	HES	1709	7.69	18.74	0	138
v_robprost	Robotic Prostatectomy volume	HES	1709	22.97	63.23	0	744
imdi	Index of Multiple Deprivation (IMD) income	HES	1707	0.11	0.05	0	0.62
charlson	Charlson Comorbidity Index	HES	1709	2.22	0.36	2	7
age	Age patients	HES	1709	63.24	4.65	2	93
ftrust	=1 if provider has Foundation Trust status	HES	1696	0.31	0.46	0	1
teaching	=1 if teaching status	ERIC	1709	0.29	0.45	0	1
occuprate	Overnight bed occupancy rate	NHS	1699	85.88	5.34	42.32	97.81
#sites	Log # sites the hospital occupies for services delivery	ERIC	1692	1.54	1.09	0	6.99
ratepop55	% Males population aged 55 and above 55 by PCT Admissionspop total admissions adjusted by population	ONS	1608	24.59	4.98	10.57	38.08
Admissionspop	total admissions adjusted by population	ONS	1601	604.18	415.26	0.65	2320.10
Urologist	# doctors performing radical prostatectomy	HES	1709	2.61	1.59	1	13
v_otherrob	Volume other robotic surgery interventions adjusted by population	HES	1709	10.06	30.39	0	255
dopen	=1 if provider only performs Open Prostatectomy	HES	1709	0.25	0.43	0	1
dopenlap	=1 if provider performs both Open and Laparoscopic Prostatectomy	HES	1709	0.21	0.41	0	1
dopenlaprob	=1 if provider performs the three interventions: Open, Laparoscopic and Robotic Prostatectomy	HES	1709	0.54	0.50	0	1

Notes: Descriptive statistics are for the sample period 2000–2018 at the hospital provider level. ESR (Electronic Staff Records), NHS Digital. ERIC (Estates Return Information Collection) from Hospital Estates and Facilities Statistics.

Table A2
Descriptive Statistics - Hospital Characteristics by NICE guidance.

		Teaching hospital	Foundation trust	Total # of sites	Admissions	Consultants (Urology)
NICE = 1	N	170	170	169	170	170
	Mean (SD)	0.553 (0.499)	0.671 (0.471)	2.267 (0.908)	647.535 (392.395)	4.106 (2.00)
	Min- Max	0–1	0–1	0.693–5.57	0.988–1543.546	1–11
NICE = 0	N	1539	1526	1523	1431	1539
	Mean (SD)	0.261 (0.439)	0.271 (0.444)	1.461 (1.082)	599.033 (417.725)	2.448 (1.446)
	Min- Max	0–1	0–1	0–6.988	0.646–2320.101	1–13

Table A3
Technology Diffusion - All Controls.

Dep. Variables	(1) Open	(2) Open	(3) Open	(4) Open	(5) Laparoscopic
Laparoscopic	−0.197***	−0.206***	−0.163***	−0.515***	
	(0.053)	(0.054)	(0.068)	(0.156)	
Robotic	−0.100***	−0.102***	−0.093***		−0.089*
	(0.032)	(0.033)	(0.040)		(0.052)
Foundation Trust (=1)	0.030	0.044	0.065	0.036	0.194
	(0.075)	(0.090)	(0.153)	(0.070)	(0.246)
Av. Index of Multiple Deprivation (Income)	−0.612	−1.019	−3.421*	−1.280	0.195
	(0.457)	(0.757)	(1.977)	(0.853)	(1.779)
Av. Charlson Comorbidity Index	0.037	0.026	0.136	−0.069	−0.126
	(0.026)	(0.043)	(0.112)	(0.083)	(0.205)
Av. Age	−0.001	0.006	0.005	0.007	0.001
	(0.003)	(0.005)	(0.012)	(0.005)	(0.016)
Bed occupancy rate	−0.002	−0.003	−0.003	−0.004	−0.007
	(0.005)	(0.006)	(0.008)	(0.005)	(0.009)
Log number of sites	−0.005	−0.009	−0.037	0.039	−0.028
	(0.021)	(0.023)	(0.025)	(0.037)	(0.032)
Percentage population >=55	−0.042	−0.051	−0.080	−0.127***	−0.025
	(0.035)	(0.039)	(0.106)	(0.037)	(0.146)
Number of admissions (over pop.)	0.001***	0.001***	0.0004**	0.001*	−2.21e-05
	(0.0002)	(0.0002)	(0.0002)	(0.001)	(0.0002)
Number of urology consultants	0.110***	0.106***	0.098***	0.114***	0.047
	(0.026)	(0.027)	(0.035)	(0.020)	(0.038)
No. Hospitals	136	81	53	79	53
N	1575	1242	613	498	613
Time fixed-effects	Yes	Yes	Yes	Yes	Yes
Providers fixed-effects	Yes	Yes	Yes	Yes	Yes
Sample: hospitals	all	open+lap/all 3	all 3	open+lap/all 3	all 3
Controls Patients	Yes	Yes	Yes	Yes	Yes
Controls Providers	Yes	Yes	Yes	Yes	Yes
R^2	0.328	0.349	0.429	0.285	0.208
Years	2000–2018	2000–2018	2000–2018	2000–2006	2006–2018

Notes: The variables on technology volumes (open, laparoscopic and robotic) are adjusted over the male population aged 55 and above (in 1000s). Robust standard errors in parentheses. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A4
Technology diffusion - teaching hospitals.

Dep. Variables	(1) Open	(2) Open	(3) Open	(4) Open	(5) Laparoscopic
Laparoscopic	−0.182**	−0.180**	−0.166*	−0.484*	
	(0.075)	(0.076)	(0.089)	(0.237)	
Robotic	−0.083**	−0.084**	−0.069*		−0.049
	(0.036)	(0.036)	(0.033)		(0.044)
Foundation Trust (=1)	0.104	0.077	0.176	0.008	0.613
	(0.145)	(0.146)	(0.177)	(0.159)	(0.369)
Ave. Index of Multiple Deprivation (Income)	−2.537**	−2.823**	−7.065	−3.131*	5.971*
	(1.056)	(1.107)	(4.241)	(1.636)	(3.283)
Av. Charlson Comorbidity Index	−0.080	−0.082	0.118	−0.322*	−0.241
	(0.064)	(0.066)	(0.222)	(0.165)	(0.442)
Av. Age	0.001	0.001	0.004	0.013*	0.011
	(0.006)	(0.007)	(0.022)	(0.007)	(0.033)
Bed Occupancy rate	0.011	0.010	0.016	−0.016	−0.019
	(0.010)	(0.010)	(0.011)	(0.012)	(0.014)
Log number of sites	0.014	0.019	−0.046	0.078	−0.073
	(0.034)	(0.034)	(0.044)	(0.121)	(0.049)
Proportion population 55+	−0.062	−0.056	−0.124	−0.109*	−0.021
	(0.058)	(0.059)	(0.223)	(0.059)	(0.312)
Total number of admissions (over pop.)	0.001	0.001	0.001	0.003	−0.0003
	(0.0003)	(0.0003)	(0.0003)	(0.002)	(0.0003)
Number of urology consultants	0.142**	0.141**	0.150**	0.128***	0.057
	(0.052)	(0.053)	(0.058)	(0.035)	(0.065)
No. Hospitals	32	27	23	26	23
N	466	439	265	162	265
Time fixed-effects	Yes	Yes	Yes	Yes	Yes
Providers fixed-effects	Yes	Yes	Yes	Yes	Yes
Sample: hospitals	all	open+lap/all 3	all 3	open+lap/all 3	all 3
Controls Patients	Yes	Yes	Yes	Yes	Yes
Controls Providers	Yes	Yes	Yes	Yes	Yes
R^2	0.347	0.375	0.454	0.342	0.248
Years	2000–2018	2000–2018	2006–2018	2000–2006	2006–2018

Notes: The variables on technology volumes (open, laparoscopic and robotic) are adjusted over the male population aged 55 and above (in 1000s). Robust standard errors in parentheses. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A5
Technology diffusion - non-teaching hospitals.

Dep. Variables	(1) Open	(2) Open	(3) Open	(4) Open	(5) Laparoscopic
Laparoscopic	−0.244**	−0.252**	−0.220*	−0.607***	
	(0.098)	(0.105)	(0.113)	(0.191)	
Robotic	−0.150**	−0.151*	−0.184*		−0.223***
	(0.074)	(0.079)	(0.092)		(0.039)
Foundation Trust (=1)	−0.013	−0.002	−0.069	0.029	−0.038
	(0.091)	(0.121)	(0.232)	(0.068)	(0.244)
Av. Index of Multiple Deprivation (Income)	0.256	0.723	−1.524	0.331	−4.061
	(0.455)	(1.007)	(2.098)	(0.747)	(2.617)
Av. Charlson Comorbidity Index	0.080***	0.130	0.609*	0.012	0.259
	(0.030)	(0.079)	(0.298)	(0.082)	(0.304)
Av. Age	−0.008*	−0.001	−0.006	−0.005	−0.014
	(0.004)	(0.010)	(0.024)	(0.007)	(0.024)
Occupancy rate	−0.005	−0.007	−0.007	−0.001	0.014
	(0.004)	(0.005)	(0.007)	(0.004)	(0.011)
Log number of sites	−0.021	−0.023	−0.047	0.038	0.005
	(0.025)	(0.030)	(0.041)	(0.029)	(0.048)
Proportion population 55+	−0.029	−0.049	−0.107	−0.139**	−0.037
	(0.046)	(0.053)	(0.099)	(0.057)	(0.089)
Total number of admissions (over pop.)	0.001***	0.001***	0.0002***	0.001*	0.0001
	(0.0002)	(0.0002)	(0.0001)	(0.0004)	(0.0001)
Number of urology consultants	0.091***	0.083***	0.065**	0.110***	0.071**
	(0.018)	(0.017)	(0.024)	(0.027)	(0.029)
No. Hospitals	104	54	30	53	30
N	1109	803	348	336	348
Time fixed-effects	Yes	Yes	Yes	Yes	Yes
Providers fixed-effects	Yes	Yes	Yes	Yes	Yes
Sample: hospitals	all	open+lap/all 3	all 3	open+lap/all 3	all 3
Controls Patients	Yes	Yes	Yes	Yes	Yes
Controls Providers	Yes	Yes	Yes	Yes	Yes
R^2	0.379	0.398	0.535	0.341	0.334
Years	2000–2018	2000–2018	2006–2018	2000–2006	2006–2018

Notes: The variables on technology volumes (open, laparoscopic and robotic) are adjusted over the male population aged 55 and above (in 1000s). Robust standard errors in parentheses. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

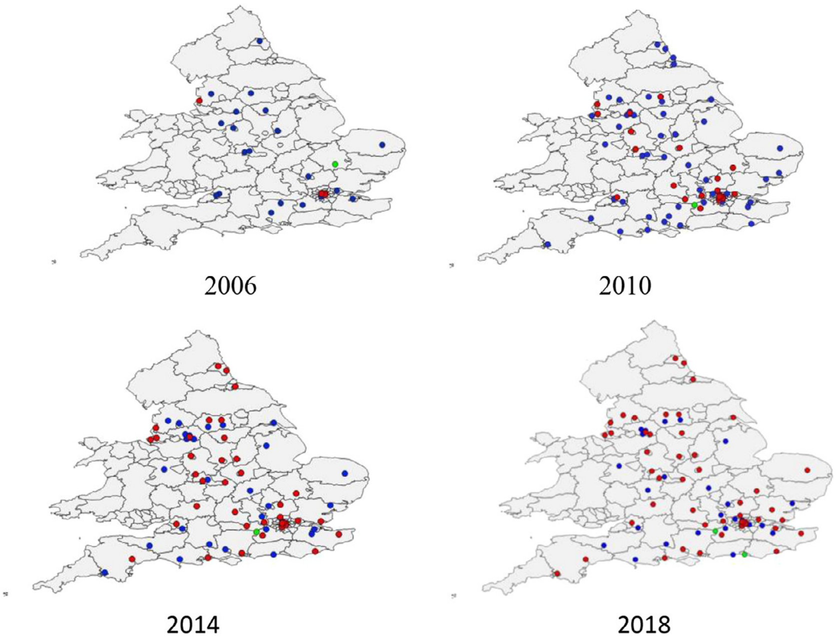

Fig. A1. Robotic surgery adoption (2006–2018). Legend: Dots represent the different providers. Blue - only Laparoscopic/Red - both, Laparoscopic and Robotic / Green - only Robotic.

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