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On May 19, 2023, PKU Institute for Globe Health and Development has launched the Survey of Medical Assessment for Robotic Technology (SMART), a longitudinal multi-center study in China. In order to ensure the SMART study progress to be updated timely and effectively among all the participants, The SMART Surgical Quarterly is launched accordingly as an internal journal. This quarterly journal will serve as a comprehensive platform to update the key information on the SMART progress as well as the progress for the parallel studies.

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平行研究

（内部交流季刊）

The Impact of Surgical Robotics on Surgical Risk and Uncertainty: A Comprehensive Economic Evaluation

By Ermo Chen*

The widespread adoption of surgical robotics in clinical practice stands in stark contrast to the inconsistent findings in health technology assessment (HTA) studies. This divergence likely stems from the inability of mean-based HTA tools to capture the risk mitigation capabilities of surgical robotics. While surgical robotics may not fundamentally alter the clinical mechanisms of certain surgeries, their standardization and stability mitigate the inherent uncertainties of human actions, potentially leading to more consistent outcomes. This distributional aspect of outcome warrants discussion in HTA evaluations.

This paper evaluates the impact of introducing surgical robotics in healthcare institutions on the risk and uncertainty of service outcomes. The variation of in hospital stay duration, clinical outcomes, postoperative complications, clinical errors and intervention costs are all incorporated into the assessment. Utilizing service records from a market-dominant surgical robotics supplier and statistical data from an IT provider covering over four thousand hospitals in China, a sample set of 4,231 hospitals with 30,936 hospital-quarters, covering 15 years (2007 - 2022) and 29 provinces is analyzed in this paper.

To analysis the overall effect on hospitals by introducing surgical robotics, the evaluation is made on model points made of hospitalquarters, because only grouped attributes contain distributional information. A time-varying difference-in-differences approach is

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introduced to identify the causal effects of introducing surgical robotics. A mixed causal inference test is used to ensure robust conclusions. And also, we developed a novel generalized linear regression method tailored for variance decomposition is proposed for a coherent framework of uncertainty analysis.

In conclusion, this paper shows that the introduction of surgical robotics significantly reduces surgical mortality rates and substantially diminishes the uncertainty associated with medical errors and postoperative complications. These benefits are under a considerable but acceptable cost. These findings underscore the importance of considering the risk-mitigating aspects of surgical robotics in economic evaluations of this health technology, which may lead consistent HTA findings.

Keywords: Medical Robot, Death Rate, Surgery

The prevalence of robotic surgery has seen a significant increase in recent years, transforming the landscape of surgical procedures. A cohort study analyzing data from 169,404 patients across 73 hospitals revealed a substantial rise in the use of robotic surgery for general procedures, increasing from 1.8% in 2012 to 15.1% in 2018 (Mehta et al., 2022). This trend indicates a broad and immediate adoption of robotic surgery, often at the expense of traditional laparoscopic minimally invasive surgery, which saw a decrease in usage.

The adoption of robotic surgery has been driven by several factors, including technological advancements and the potential for improved precision and control during operations. A review article highlighted the evolution of robotic surgery from skepticism to becoming a standard of care (George et al., 2018). The integration of robotics in surgery has been facilitated by developments such as the Da Vinci Surgical System, which allows for complex procedures with enhanced dexterity and a three-dimensional view.

Despite the technological advancements, concerns regarding the cost-effectiveness of robotic surgery persist. Some studies have suggested that robotic surgery may be more costly than traditional laparoscopic surgery, without always providing additional clinical benefits. For instance, the FDA has issued warnings against the use of robotic surgery for certain cancer treatments due to a lack of evidence supporting its efficacy (Food and

Administration, 2023).

The clinical benefits of robotic surgery are still a subject of debate. While some studies have reported improved outcomes in specific procedures, such as roboticassisted liver resection (Lafaro et al., 2020), others have found no significant difference in outcomes when compared to laparoscopic or open surgery. A metaanalysis comparing robot-assisted liver resection to laparoscopic liver resection found no significant differences in clinical outcomes (D´ıaz et al., 2015).

The rapid growth of robotic surgery has also raised questions about the training and expertise required for surgeons to effectively utilize these advanced technologies. The learning curve associated with robotic surgery is a critical factor in determining its effectiveness and safety. Additionally, the economic implications of adopting robotic surgery, including the impact on healthcare costs and resource allocation, are significant considerations for hospitals and healthcare systems.

In conclusion, while robotic surgery has shown promise in enhancing surgical precision and patient outcomes in certain contexts, its increasing prevalence raises important questions about cost, efficacy, and the need for ongoing evaluation of its role in various surgical procedures. The surgical community and regulatory bodies must continue to monitor the adoption of robotic surgery to ensure that its use is supported by robust clinical evidence and that it contributes positively to patient care.

The impact of robotic surgery on clinical outcomes has been a subject of considerable debate, with studies yielding both positive and negative results. While some research indicates that robotic surgery can lead to improved precision and reduced postoperative complications, other studies suggest that it may not always offer significant benefits over traditional surgical methods and can sometimes result in higher costs and longer operative times. A systematic review and metaanalysis by Kowalewski et al. (Kowalewski et al., 2021) compared laparoscopic and robotic-assisted rectal resection, finding no significant differences in most clinical outcomes. However, they noted that robotic surgery was associated with a higher cost, raising questions about its cost-effectiveness. Similarly, a study by Bongiolatti et al. (Bongiolatti et al., 2020) on robot-assisted minimally invasive esophagectomy found no significant differences in oncological outcomes between robotic and open surgery, but highlighted the need for further research to validate the benefits of robotic surgery.

On the positive side, Ramirez et al. (Ramirez et al., 2017) reported that minimally invasive radical hysterectomy using robotic assistance resulted in fewer conversions to open surgery compared to laparoscopic methods. Additionally, a systematic review by

Vijayakumar et al. (Vijayakumar et al., 2020) in the field of oncology suggested that robotic surgery could offer improved outcomes, although they also noted the need for more rigorous research to support these findings.

Conversely, a study by Audenet et al. (Audenet et al., 2020) found evidence of atypical recurrences after robot-assisted radical cystectomy, indicating potential risks associated with robotic surgery. O'Sullivan et al. (O'Sullivan et al., 2018) conducted a meta-analysis of lobectomy approaches and found no significant differences in outcomes between robotic, video-assisted thoracoscopic, and open surgery, suggesting that robotic surgery may not always provide superior results.

The inconsistent impact of robotic surgery on clinical outcomes is further highlighted by a systematic overview of reviews by Muaddi et al. (Muaddi et al., 2021), which found that while robotic-assisted radical prostatectomy offered some benefits, such as fewer biochemical recurrences and improved quality of recovery, these were only observed up to six weeks postoperatively. The authors concluded that more research is needed to determine the true value of robotic surgery.

In summary, the literature suggests that while robotic surgery has the potential to offer certain benefits, such as improved precision and reduced conversion rates, it is not universally superior to conventional surgical approaches. The decision to adopt robotic surgery should be based on a careful evaluation of its clinical benefits, cost-effectiveness, and the availability of robust evidence supporting its use (Kowalewski et al., 2021; Bongiolatti et al., 2020; Ramirez et al., 2017; Vijayakumar et al., 2020; Audenet et al., 2020; O'Sullivan et al., 2018; Muaddi et al., 2021).

In summary, prior works does not show coherent significantly benefit on surgeries with introducing medical robots (Borden et al., 2007). while in real world it does become more and more popular. More driving factors need to be excavated. Too few samples to draw reliable result beyond expectation, such as risk and uncertainty, in cohort studies. This force us to use larger data sets in a retrospective way.

We investigate the effect on death rate changes by introducing medical robots. Prior works does not show coherent significantly benefit on surgeries with introducing medical robots, see Borden et al. (2007) and Alemzadeh et al. (2016), while in real world it does become more and more popular. More driving factors need to be excavated. Too few samples to draw reliable result beyond expectation, such as risk and uncertainty, in cohort studies. This force us to use larger data sets in a retrospective way. Prior works does not show coherent significantly benefit on surgeries with intro- ducing medical robots (Borden et al., 2007). while in real world it does become more and more popular. More driving factors need to be excavated. Too few samples to draw reliable result beyond expectation, such as risk and uncertainty, in cohort studies. This force us to use larger data sets in a retrospective way.

We investigate the effect on death rate changes by introducing medical robots. Results show that the medical robot can lead significantly reduce on death rate of surgery. This is part of the project of researches on medical errors.Results show that the medical robot can lead significantly reduce on death rate of surgery. This is part of the project of researches on medical errors.

I. Data

A. Data sources

Service record from a market-dominating medical robot provider, with all its service records in mainland China. It recorded the name of hospital, surgery date and category of surgery of each case.

Statistical records from a info-tech provider are provided by a inner statistical report, with samples covering 2007-2022 calendar years and 6252 hospitals in mainland china. Number of Samples, Death rate, Average Cost, Variance of Cost and In-hospital Days are reported for each hospital each month and each category of surgery or division. The location, level and grade of the hospitals are also accessible.

These two sources could be merged with hospital and date, making the analysis feasible. 6252 hospitals are covered in the analysis, containing 97 hospitals with medical robots using records, covering 28328/314152 = 9% of all the service record in robot provider. With a data filter, 4231 hospitals with 30936 hospital-quarters are finally used in drawing statistical conclusions.

B. Filter Settings and Reasons

The regression will not get stable result unless using the statistics of model points with sample sizes larger than a hurdle level.

We use a common regression

$$\mathrm{ExpecedCost}_{i,t} \sim \mathrm{X}_i + \mathrm{I}_t + \mathrm{SampleSize}_{i,t}, \tag{1}$$

which modeling the cost effect in areas and periods. A reasonable result should shows that the cost increasing along time, and positive diffs from large city to low-income areas. The Figure below shows the estimation of coefficients, using different hurdle level on sample sizes.

Stable and reasonable results generate for estimations with model points larger than 30 samples. In our paper, we use model points larger than 50 samples for reliable results.

II. Cross-sectional Analyses

A. Effect on death rate

The regression model in this section is

$$\mathrm{DeathRate}_{i,t} \sim \mathrm{Robot}_{i,t} + \mathrm{X}_i + \mathrm{I}_t, \quad \omega = \mathrm{SampleSize}_{i,t} \quad , \tag{2}$$

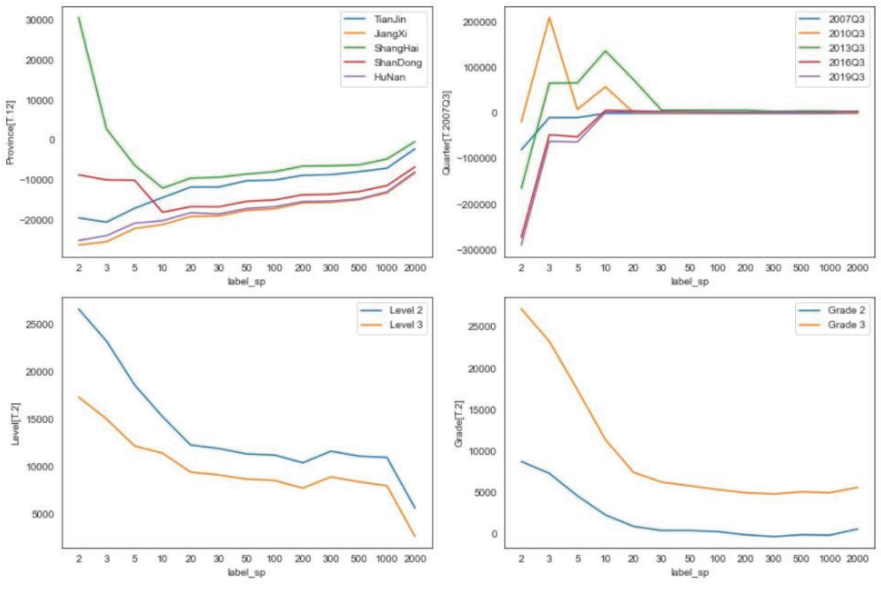

Figure 1. Estimation Of Coefficients

where we use two kinds of variables measuring the level of introducing robots, the number of cases down with robots, and the rate of cases down with robots w.r.t. the sample size (robot rate). This is because that the statistical record data are drawn on samples but not fully records, making the evaluation of robot rate not accurate enough. However, the robot rate is necessary to evaluate the level of effect beyond a signature judgement. So both of them are considered in the process of analysis.

Two kinds of fix effected for hospitals are considered. One is to use the unique ID of hospital directly, which is simple by constrained by some missing result in statistical result data. The other one is to use the province, level and grade instead, with may loss some information but more reliable. We check the result of both options, for robustness and reducing endogeneity.

Results of accounting amount of surgery cases done with robots are shown as below in Table II.A.

The result showed significantly negative relationship between robot surgery count and death rate, under the control of fix effect of time and hospital (both directly and indirectly). Without the control of fix effect, especially the hospital effect, the result becomes complex. This is caused by the selection bias on introducing robots among hospitals, which is common as it is very expensive.

	Hospital Level, Robot Count			
Num_of_Robot	1.65E-06	1.12E-06	**-6.19E-06**	**-2.12E-06**
p-Value: Num_of_Robot	0.0838	0.2436	**0.0000**	**0.0094**
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin				
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_ Grade			Yes	
Num of Model Points	30,936	30,936	30,936	30,936
F-stats	2.9890	5.1351	100.2786	17.8164
R-squared	0.0001	0.0104	0.2454	0.7417

Results of accounting amount of proportion of surgery cases done with robots w.r.t. sample cases in model points are shown as below in TableII.A.

	Hospital Level, Robot Rate			
Robot_Rate	2.27E-02	1.79E-02	**-2.88E-02**	**3.10E-02**
p-Value: Robot_Rate	0.1020	0.1960	**0.0184**	**0.0057**
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin				

Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_Grade			Yes	
Num of Model Points	30,936	30,936	30,936	30,936
F-stats	2.6734	5.1401	99.6580	17.8172
R-squared	0.0001	0.0104	0.2443	0.7417

Similar results could be drawn from this analysis about proportion, while things changes as the fixed effect is chosen directly using hospital ID. This is because that the data of robot service is full covered, but the statistical results are sampled. It then will disturb the evaluate of measuring real robot rate, as the denominator is not reliable. So the result on the robot surgery count is more reliable in judging the direction of robot effect.

Similar analysis are done with the statistical results data separating divisions for different surgeries. The results are shown as Table II.A for robot counts below.

	Division Level, Robot Count			
Num_of_Robot	-9.06E-07	-5.88E-07	**-4.07E-06**	**-1.97E-05**
p-Value: Num_of_Robot	0.5228	0.6820	**0.0105**	**0.0000**
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin	Yes	Yes	Yes	Yes
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_ Grade			Yes	
Num of Model Points	12,849	12,849	12,849	12,849
F-stats	109.2986	12.6725	13.3416	8.6823
R-squared	0.0638	0.0649	0.0999	0.6055

And Table II.A for robot rates.

Coherent conclusions with former regression result

	Division Level, Robot Rate			
Robot_Rate	-1.39E-03	-8.91E-04	**-5.97E-03**	**-1.38E-02**
p-Value: Robot_Rate	0.5963	0.7368	**0.0351**	**0.0000**
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin	Yes	Yes	Yes	Yes
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_Grade			Yes	
Num of Model Points	12,849	12,849	12,849	12,849
F-stats	109.2816	12.6717	13.3194	8.6144
R-squared	0.0637	0.0649	0.0998	0.6036

B. Effect on in-hospital days

The regression model in this section is

$$(3) \qquad \mathrm{InHospitalDays}_{i,t} \sim \mathrm{Robot}_{i,t} + \mathrm{X}_i + \mathrm{I}_t, \quad \omega = \mathrm{SampleSize}_{i,t},$$

where modelling the length of stay in hospital. Other settings are similar with the former section.

Results are displayed as below, firstly is the result with hospital level statistics on robot case counts.

	Effect on in-hospital days			
Num_of_Robot	-1.33E-01	-9.52E-02	-2.99E-02	7.37E-01
p-Value: Num_of_Robot	0.8756	0.9121	0.9729	0.5969
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin				
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_Grade			Yes	
Num of Model Points	30,904	30,904	30,904	30,904
F-stats	0.0245	0.2178	0.9134	0.3736

R-squared	0.0000	0.0004	0.0030	0.0568

Secondly, there is the result with hospital level statistics on robot case proportions.

	Effect on in-hospital days			
Robot_Rate	-1.13E+03	-7.70E+02	-2.00E+02	3.91E+03
p-Value: Robot_Rate	0.9277	0.9508	0.9873	0.8382
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin				
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_Grade			Yes	
Num of Model Points	30,904	30,904	30,904	30,904
F-stats	0.0082	0.2177	0.9134	0.3735
R-squared	0.0000	0.0004	0.0030	0.0568

And similar results with division level shown as below two tables.

It shows that, no significant changes are shown in the results, means that the length in hospital will not be effected heavily with introducing the robot for surgeries. This is coherent with the conclusions of other researches.

	Effect on in-hospital days			
Num_of_Robot	-4.04E-03	5.79E-02	1.57E-01	5.42E-01
p-Value: Num_of_Robot	0.9969	0.9561	0.8945	0.8309
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin	Yes	Yes	Yes	Yes
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_Grade			Yes	
Num of Model Points	12,847	12,847	12,847	12,847
F-stats	2.0274	0.2798	0.3284	0.1813
R-squared	0.0013	0.0015	0.0027	0.0311

	Effect on in-hospital days			
Robot_Rate	-8.98E+00	9.68E+01	2.20E+02	5.22E+02
p-Value: Robot_Rate	0.9963	0.9602	0.9169	0.8716
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin	Yes	Yes	Yes	Yes
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_ Grade			Yes	
Num of Model Points	12,847	12,847	12,847	12,847
F-stats	2.0274	0.2798	0.3283	0.1813
R-squared	0.0013	0.0015	0.0027	0.0311

C. Effect on cost expectation

The regression model in this section is

$$\text{ExpectedCost}_{i,t} \sim \text{Robot}_{i,t} + \text{X}_i + \text{I}_t, \quad \omega = \text{SampleSize}_{i,t}, \tag{4}$$

where modelling the expected cost. Other settings are similar with the former section.

Results are shown as below.First is the results on robot surgery case numbers.

	Effect on cost expectation			
Num_of_Robot	2.72E+01	2.63E+01	1.93E+01	3.34E+00
p-Value: Num_of_Robot	0.0000	0.0000	0.0000	0.0017
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin				
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_Grade			Yes	
Num of Model Points	30,936	30,936	30,936	30,936
F-stats	744.2504	17.9099	113.2246	9.5432
R-squared	0.0235	0.0353	0.2686	0.6060

Second is the the results on robot surgery case proportions.

	Effect on cost expectation			
Robot_Rate	3.47E+05	3.37E+05	2.67E+05	1.18E+05
p-Value: Robot_Rate	0.0000	0.0000	0.0000	0.0000
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin				
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_ Grade			Yes	
Num of Model Points	30,936	30,936	30,936	30,936
F-stats	564.6737	15.4653	112.8116	9.5755
R-squared	0.0179	0.0306	0.2679	0.6068

Both groups of results show significant increment in cost when introducing the robot. This is common as it does take some more cost using the machine, such as start-up fee, equipment fee, maintenance fee.

D. Effect on cost uncertainty

The regression model in this section is

$$(5)\quad \mathrm{VarianceCost}_{i,t} \sim \mathrm{Robot}_{i,t} + \mathrm{Robot}_{i,t}(1-\mathrm{Robot}_{i,t}) + \mathrm{X}_{i} + \mathrm{I}_{t},\ \omega = \mathrm{SampleSize}$$

where modelling the variance of cost. Other settings are similar with the former section. The term of $\mathrm{Robot}_{i,t}(1-\mathrm{Robot}_{i,t})$ is used to separate the Within-group variance from the total variance. We proof the reason of this method in appendix.

In this section, only proportion of robot is available, as the number of robot could not face the constrains of variance regression theory.

The results are shown as below. First is the result on hospital level statistics.

	Effect on cost uncertainty			
Robot_Rate	3.71E+12	1.85E+12	-1.34E+12	-6.30E+12
p-Value: Robot_Rate	0.9400	0.9702	0.9784	0.9318
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin				
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_Grade			Yes	
Num of Model Points	30,936	30,936	30,936	30,936
F-stats	0.0185	0.4753	0.6423	0.7605
R-squared	0.0000	0.0010	0.0021	0.1092

Second is the result on division level statistics.

	Effect on cost uncertainty			
Robot_Rate	-1.43E+13	-1.07E+13	-3.34E+12	3.72E+12
p-Value: Robot_Rate	0.9398	0.9553	0.9869	0.9919
Fix Effect: Time		Yes	Yes	Yes
Fix Effect: Hospital				Yes
Fix Effect: Divisioin	Yes	Yes	Yes	Yes
Fix Effect: Province			Yes	
Fix Effect: Hospital_Lv			Yes	
Fix Effect: Hospital_Grade			Yes	
Num of Model Points	12,849	12,849	12,849	12,849
F-stats	0.0825	0.0397	0.0445	0.0589
R-squared	0.0001	0.0002	0.0004	0.0103

We can claim that there is no significant difference between robot surgeries and traditional ones.

III.Time-Varying Difference-in-difference Analyses

In this section, we build a time-varying difference-in-difference model to judge that if the attribute observed above is actually caused by the introduction of surgical robots. Similarly, we use model points as hospital × quarter, and a treatment trigger labeled by if has already introduced the surgical robots for some of the surgeries.

For models except the ones on variance, the regression equation are designed as

$$\text{Measure}_{i,t} = \alpha + \mu_i + \lambda_t + \theta \text{Robot\_Rate}_{i,t} \times \text{Post}_{i,t} + \text{X}_i, \tag{6}$$

where $\text{Measure}_{i,t}$ is the target measure, which could be represented as ’Death Rate’, ’Average In-hospital Days’ and ’Expectation Cost’. And also, Post_t represents for if the model point is already under treatment, which means

$$\text{Post}_{i,t} = \text{I}(\text{Robot\_Rate}_{i,t} > 0)$$

For models on variance, the regression equation are designed as

$$\begin{aligned} \text{Variance}_{i,t} = \alpha + \mu_i + \lambda_t + \theta_1 \text{Robot\_Rate}_{i,t} \times \text{Post}_{i,t} \\ + \theta_2 \text{Robot\_Rate}_{i,t}(1 - \text{Robot\_Rate}_{i,t}) \times \text{Post}_{i,t} + \text{X}_i, \end{aligned} \tag{7}$$

with all other settings the same.

Table 1—Effect on Cost Expectation by introducing Surgical Robot

	(1)	(2)	(3)	(4)
	cost_exp	cost_exp	cost_exp	cost_exp
	90858.039***	67088.417*	64013.461*	63159.306*
	(27176.581)	(37267.088)	(34551.897)	(35230.905)
hospital level	Controlled	-571.574***		-477.949***
		(59.393)		(60.474)
grade		1597.509***		1539.725***
		(164.393)		(148.454)
Province cons	7959.176***	5215.464***	23148.462***	Controlled 19944.458***
	(1884.634)	(1847.924)	(3502.365)	(3627.37)
Observations	30936	30936	30936	30936

IV. Conclusion

In summary, one can show that both in cross-sectional analysis and DID results, the effects on outcome by introducing surgical robots into hospitals are similar. The major findings are shown as below.

TABLE 2—EFFECT ON IN-HOSPITAL STAY LENGTH BY INTRODUCING SURGICAL ROBOT

	(1)	(2)	(3)	(4)
	inhos_exp	inhos_exp	inhos_exp	inhos_exp
	670.501	-475.142	88.884	32.562
	(873.401)	(467.394)	(182.644)	(214.883)
hospital level	Controlled	-44.583		-21.735
		(44.362)		(21.192)
grade		122.15		128.314
		(113.373)		(118.296)
Province cons	2171.183		127.005*	Controlled
		-203.805		-188.545
	(1671.862)	(199.519)	(71.862)	(247.309)
Observations	30904	30904	30904	30904

TABLE 3—EFFECT ON DEATH RATE BY INTRODUCING SURGICAL ROBOT

	(1)	(2)	(3)	(4)
	death_rate	death_rate .031	death_rate	death_rate .026
	-.05***		.026	
	(.014)	(.021)	(.024)	(.024)
hospital level	Controlled	0		0
		(0)		(0)
grade		0		0
		(0)		(0)
Province cons			.012**	Controlled
	.005	.005		.011**
	(.005)	(.005) 30936	(.005)	(.005)
Observations	30936		30936	30936

TABLE 4—EFFECT ON COST VARIATION BY INTRODUCING SURGICAL ROBOT

	(1)	(2)	(3)	(4)	(5)
	cost_var	cost_var	cost_var	cost_var	cost_var
	1.846e+11	-3.172e+11	1.027e+11	7.298e+10	-6.194e+13
	(3.761e+11)	(3.121e+11)	(1.135e+11)	(9.318e+10)	(6.001e+13)
hospital level	Controlled	-1.560e+10		-1.388e+10	1.925e+11
		(1.278e+10)		(1.009e+10)	(1.406e+11)
grade		5.527e+10		5.204e+10	-9.663e+11
		(5.575e+10)		(5.632e+10)	(6.829e+11)
Province				Controlled	Controlled
cost_exp					4.601e+08
					(3.234e+08)
_cons	9.831e+10***	-1.070e+11	1.234e+10	-1.081e+11	-8.482e+12
	(3.096e+10)	(1.163e+11)	(1.822e+10)	(1.248e+11)	(6.204e+12)
Observations	30936	30936	30936	30936	30936

- Surgery Robots will help reducing the death rate in hospital significantly.
- Although the average cost has a significant increment, the variance is somehow under control.
- The length in hospital is not significantly effected.

In conclusion, this paper shows that the introduction of surgical robotics significantly reduces surgical mortality rates and substantially diminishes the uncertainty associated with medical errors and postoperative complications. These benefits are under a considerable but acceptable cost. These findings underscore the importance of considering the risk-mitigating aspects of surgical robotics in economic evaluations of this health technology, which may lead consistent HTA findings.

V. Declaration

This is still a processing version, the finally result could be different.

Proof of Variance Regression Theory

One could not directly use the regression on proportion to estimate the effect on total variance, if there is difference both on expectations and variances. So we propose this specially designed regression for this propose.

We have

$$X_i \sim \mathbb{E}[X_i] = \mu_1, \quad \mathrm{Var}[X_i] = \sigma_1^2, \forall i \tag{A1}$$

and

$$Y_j \sim \mathbb{E}[Y_j] = \mu_2, \quad \mathrm{Var}[Y_j] = \sigma_2^2, \forall j, \tag{A2}$$

say *X* for other surgeries and *Y* for robot ones for example. We have model points' result of variance, with N_1 cases of *X* and N_2 cases of *Y* in some unique model point. We know the variance is indeed evaluated as the following equation, although we could not get the detailed data.

$$\begin{aligned}\mathrm{Var}[Z] &= \frac{1}{N-1}\left[\sum_{i=1}^{N_1}\left(X_i - \frac{\sum_{i=1}^{N_1} X_i + \sum_{j=1}^{N_2} Y_j}{N}\right) + \sum_{j=1}^{N_2}\left(Y_j - \frac{\sum_{i=1}^{N_1} X_i + \sum_{j=1}^{N_2} Y_j}{N}\right)\right] \\ &= \frac{1}{N-1}\left(\sum_{i=1}^{N_1} X_i^2 + \sum_{j=1}^{N_2} Y_j^2 - \frac{1}{N}(\sum_{i=1}^{N_1} X_i + \sum_{j=1}^{N_2} Y_j)^2\right),\end{aligned} \tag{A3}$$

where N = N1 +N2 .

Then we can get

$$\begin{aligned}\mathbb{E}[\mathrm{Var}[Z]] &= \frac{1}{N-1}\left[N_1(\mu_1^2+\sigma_1^2) + N_2(\mu_2^2+\sigma_2^2) - \frac{1}{N}\mathbb{E}[(\sum_{i=1}^{N_1} X_i + \sum_{j=1}^{N_2} Y_j)^2]\right] \\ &= \frac{1}{N-1}\left[N_1(\mu_1^2+\sigma_1^2) + N_2(\mu_2^2+\sigma_2^2) - \frac{1}{N}\left(N_1(\mu_1^2+\sigma_1^2) + N_2(\mu_2^2+\sigma_2^2)\right)\right] \\ &+ \frac{1}{N-1}\left[\frac{1}{N}\left(N_1(N_1-1)\mu_1^2 + N_2(N_2-1)\mu_2^2 + 2N_1N_2\mu_1\mu_2\right)\right] \\ &= \frac{N_1}{N}(\mu_1^2+\sigma_1^2) + \frac{N_2}{N}(\mu_2^2+\sigma_2^2) - \frac{N_1}{N}\frac{N_1-1}{N-1}\mu_1^2 - \frac{N_2}{N}\frac{N_2-1}{N-2}\mu_2^2 - 2\frac{N_1}{N}\frac{N_2}{N}\mu_1\mu_2.\end{aligned} \tag{A4}$$

Use $\frac{N_2}{N} = \lambda$ for simplification, and under the assumption that

$$N_1 \ll N_2 \ll 1, \tag{A5}$$

which is suitable for our case, we can get

(A6)
$$\frac{N_1}{N} = 1 - \lambda,\ \frac{N_2 - 1}{N - 1} \approx \lambda,\ \frac{N_1 - 1}{N - 1} \approx 1 - \lambda.$$

Then we can finally get

(A7)
$$\begin{aligned}\mathbb{E}[\mathrm{Var}[Z]] &= [\sigma_2^2 - \sigma_1^2 + (\mu_2 - \mu_1)^2]\lambda - (\mu_2 - \mu_1)^2\lambda^2 + c \\ &= (\sigma_2^2 - \sigma_1^2)\lambda + (\mu_2 - \mu_1)^2[\lambda(1 - \lambda)] + c\end{aligned}$$

where c is independent with λ .

This means that we can regression $\mathbb{E}[\mathrm{Var}[Z]]$ with λ and λ(1 − λ) to get the estimation and test result of $\sigma_2^2 - \sigma_1^2$.

(A8)
$$\mathcal{H}_0 : \sigma_1^2 \leq \sigma_2^2 \quad v.s. \quad \mathcal{H}_1 : \sigma_1^2 > \sigma_2^2$$

(A9)
$$X \sim Y_2 + \epsilon_1 \quad \rightarrow \quad \hat{X}$$

(A10)
$$\frac{N_1}{N} = 1 - \lambda,\ \frac{N_2 - 1}{N - 1} \approx \lambda,\ \frac{N_1 - 1}{N - 1} \approx 1 - \lambda.$$

(A11)
$$\hat{\beta}_\delta \sim \delta + \epsilon_0 \quad \rightarrow \quad \alpha_\delta,\ k_\delta$$

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Robot Adoption in Chinese Hospitals: Progress Report

By Kwanting Leung Yuhang Pan*

We empirically examine the impact of the first-time using of medical robots on department level performance in China. Employing a robust analytical framework combining Two-Way Fixed-Effect (TWFE) and Event Study methodologies, we analyze daily department data spanning from Jan 2013 to Dec 2022. Our focus is on quantifying the shifts in ln total revenue following the first-time using of this advanced surgical technology.

Due to its unprecedent economic development and increasingly growing demands, China has become one of the fastest-growing markets for the surgical robotics developer. This short article briefly reviews the technology adoption of da Vinci surgical system (da Vinci RAS) in Chinese hospitals, especially at the hospital department level. As of 2022, da Vinci RAS was recognized as the largest provider of robotic-assisted surgical (RAS) technology training to be accredited, and nearly 7000 da Vinci RAS have been installed in more than 70 countries, with more than 10 million minimally invasive robotic surgical procedures performed (Xue et.al, 2021).

The da Vinci surgical system was first introduced in China in 2006, where it was adopted at Chinese PLA General Hospital. Over the period from 2006 to 2023, a total of 284 Chinese hospitals have implemented the da Vinci RAS system. This technology has then been utilized by approximately 2,300 surgeons among a diverse range of surgical procedures. These surgeons have performed over 180 kinds of procedures, with the highest volume observed in Urology at around 150 thousand procedures.

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We thank Da Vinci for providing the market data. All errors are our own.

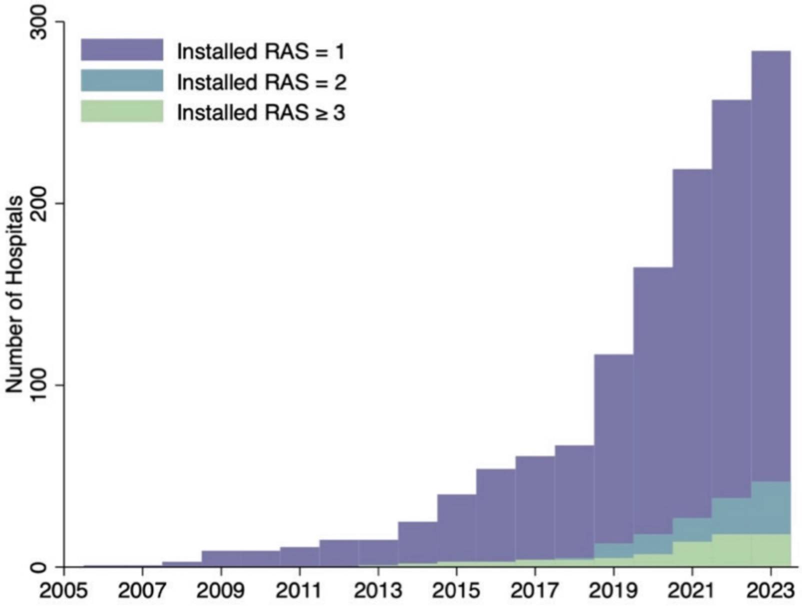

FIGURE 1. NUMBER OF CHINESE HOSPITALS WITH DA VINCI RAS

The adoption of da Vinci systems in Chinese hospitals encompasses four distinct models: DaVinci SP, DaVinci S, DaVinci Si, and DaVinci Xi. Our focus lies in examining the inaugural procedures performed using the da Vinci system within each category and across various hospital-department pairings. Figure 1 depicts the prevalence of da Vinci RAS systems across Chinese hospitals. Two notable periods of growth are observed. The first eye-catching growth occurred in 2014, where the number of hospitals with the da Vinci system nearly doubled. The second substantial growth took place around 2019, resulting in a rise from 69 hospitals to 119 hospitals with da Vinci systems.

Figure 2 illustrates the time lag between the installation of the da Vinci RAS system and its initial application across various surgical departments. The data suggest that General Surgery and Urology departments show a short interval from system installation to operation, possibly due to the high demands and immediate applicability of the da Vinci RAS for procedures common to these fields. The da Vinci RAS system is leveraged for an extensive array of procedures. For Urology, it can perform oncological management of prostate, kidney, and bladder cancers. In the sphere of General Surgery, the RAS system is for intricate removal of gastrointestinal malignancies, including gastric and colorectal cancers. Thoracic Surgery harnesses the advanced capabilities of the RAS for conditions like lung and esophageal cancers. For Gynecology, the da Vinci can be used to hysterectomies and managing gynecologic cancers. Building upon the classification initiated in Figure 2, the analysis extends to the level of hospital departments, incorporating additional specialties such as Pediatrics, Gastroenterology, Hepatobiliary Pancreatic, and Thyroid. As presented in Figure 3, only the Thyroid department exhibited a notable delay between the installation of RAS systems and their operational use, suggesting a latent phase of adoption for certain specialties.

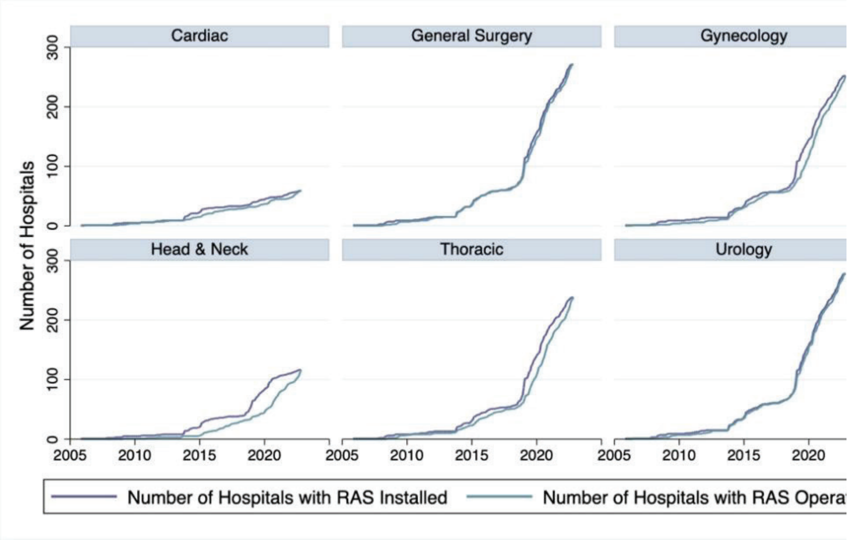

Figure 2. Installation And Operation Of Ras By Category

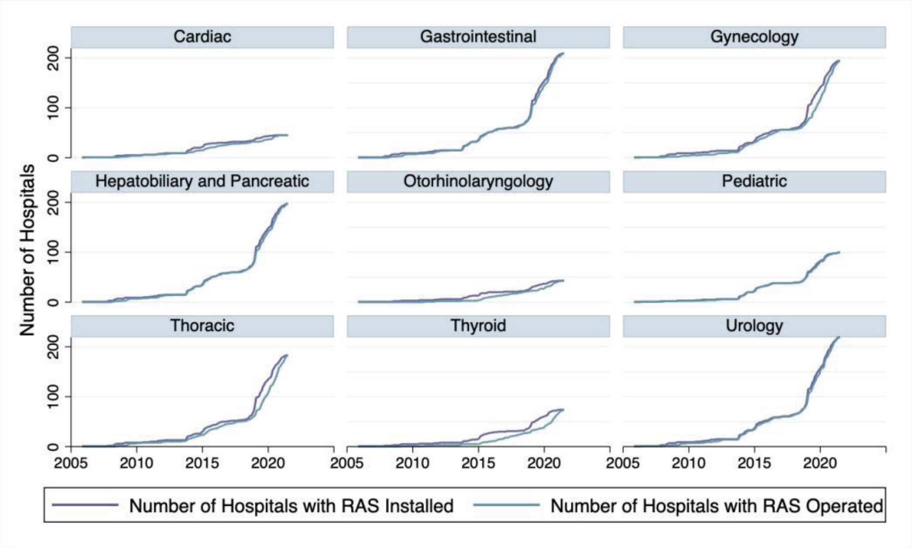

Figure 3. Installation And Operation Of Ras By Hospital Departments

Data

The patient-level data, with each observation representing information for a single patient's entire stay, is aggregated at the department level daily. The data includes patient characteristics, spending, length of stay, and dates of admission and discharge.

Due to the lack of information on daily patient payments, we make three assumptions regarding how hospitals collect these payments. First, the hospital collects an equal amount daily; second, the hospital collects a lump sum on the date of admission; third, the hospital collects a lump sum on the date of discharge.

Assuming that patients spend the same amount of money each day during admission, daily revenue is calculated by using their total spending divided by the length of stay. Assuming that the hospital charges once at admission, total revenue on the admission date is calculated by adding up the total spending of each patient on the date of admission. Assuming that the hospital charges once at discharge, total revenue on the discharge date is calculated by adding up the total spending of each patient on the date of discharge.

The two-digit number Age Gender contains information about the patient's gender and age. Gender includes 1 for male, 2 for female, and 3 for unknown. Six age groups are assigned: 0-15, 16-30, 31-45, 46-60, 61-75, and above 76. Three types of patient characteristics are calculated: first, cumulative for all patients currently in the hospital; second, for patients who have just been admitted; third, for discharged patients.

Summary Statistic

The summary statistics presented in Table 1 provides an overview of hospital-level metrics across the control and the treatment groups, segmented by month and week levels. Key indicators include average length of stay, number of patients, department level death rate, total revenue, self-pay revenue, and nursing revenue, all measured over the period from January 2013 to December 2022.

The mean number of patients admitted is substantially higher in the treated group, suggesting that hospitals with the da Vinci system may handle more complex or advanced cases or these hospitals with da Vinci are generally San Jia hospital with larger compacity for more patients. Although treatment group on average have 2.5 times patients compare to control group, they make almost 4.7 times more on department total income, total self-pay, and nursing revenue.

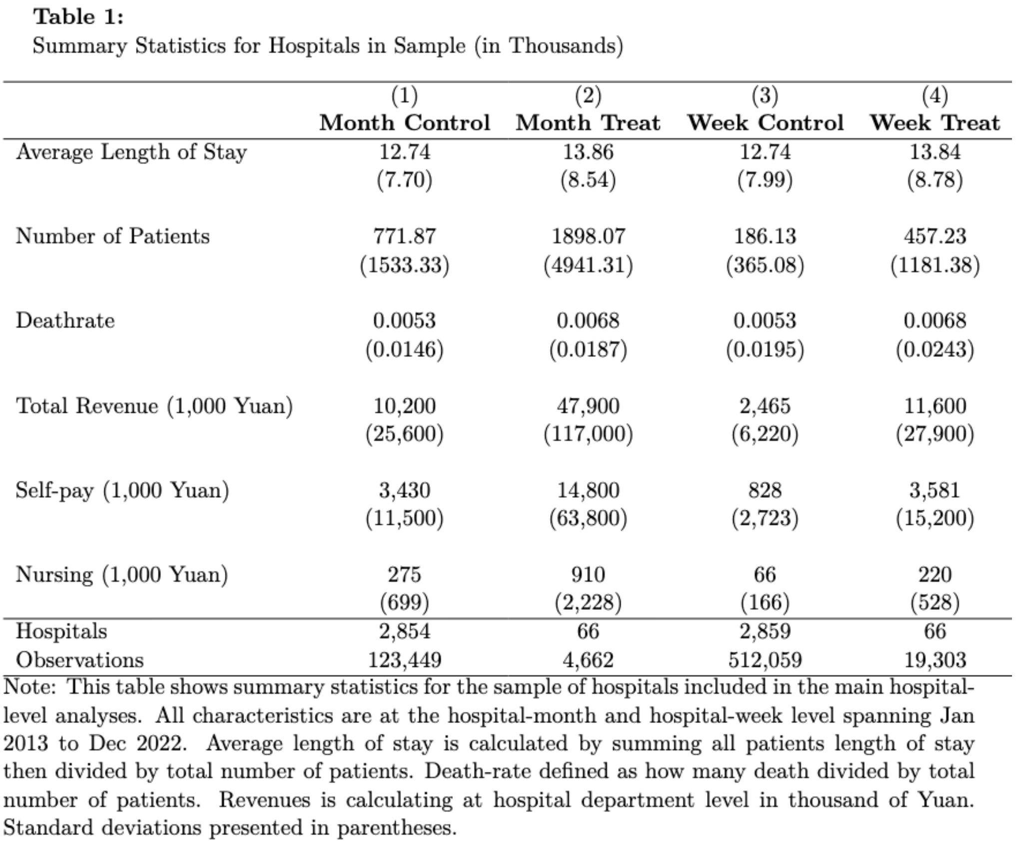

Table 1:
Summary Statistics for Hospitals in Sample (in Thousands)

	(1) **Month Control**	(2) **Month Treat**	(3) **Week Control**	(4) **Week Treat**
Average Length of Stay	12.74	13.86	12.74	13.84
	(7.70)	(8.54)	(7.99)	(8.78)
Number of Patients	771.87	1898.07	186.13	457.23
	(1533.33)	(4941.31)	(365.08)	(1181.38)
Deathrate	0.0053	0.0068	0.0053	0.0068
	(0.0146)	(0.0187)	(0.0195)	(0.0243)
Total Revenue (1,000 Yuan)	10,200	47,900	2,465	11,600
	(25,600)	(117,000)	(6,220)	(27,900)
Self-pay (1,000 Yuan)	3,430	14,800	828	3,581
	(11,500)	(63,800)	(2,723)	(15,200)
Nursing (1,000 Yuan)	275	910	66	220
	(699)	(2,228)	(166)	(528)
Hospitals	2,854	66	2,859	66
Observations	123,449	4,662	512,059	19,303

Note: This table shows summary statistics for the sample of hospitals included in the main hospital-level analyses. All characteristics are at the hospital-month and hospital-week level spanning Jan 2013 to Dec 2022. Average length of stay is calculated by summing all patients length of stay then divided by total number of patients. Death-rate defined as how many death divided by total number of patients. Revenues is calculating at hospital department level in thousand of Yuan. Standard deviations presented in parentheses.

Empirical Model

In this section, we present the empirical analysis to assess the impact of the first-time usage of the da Vinci Surgical System on various departmental outcomes. Our analysis employs a Difference-in-Differences (DID) approach, leveraging a panel dataset of hospitals and departments to estimate the causal effects of this advanced surgical technology. Below, we outline the empirical model, discuss our identification strategy, and summarize the main findings.

We estimate the impact of the da Vinci Surgical System installation using a generalized DID approach, where our outcome variables $\mathrm{Y}_{\mathrm{i,j,t}}$ are regressed on a set of event-time dummies representing the periods before and after the installation. The model is specified as follows: (He and Wang, 2017)

$$Y_{i,j,t} = \alpha + FirstProc_{i,j,t} + \rho_{i,j} + \vartheta_t + \epsilon_{i,j,t}$$

where $Y_{i,j,t}$ is the outcome for hospital i department j in year t, $\mathrm{FirstProc}_{i,j,t}$ is a dummy indicator that equals 1 if hospital i department j in year t has started to use the da Vinci robotic system, and 0 otherwise. ϑ_t is the fixed effect on time, and $\rho_{i,j}$ is the fixed effect on hospital departments. Standard errors are clustered at hospital and department level.

The DID identification strategy relies on the variation in the timing of the da Vinci system first-time using across hospitals and departments. By comparing the outcomes of departments before and after the installation or first-use, and against departments that have not yet adopted the system, the DID approach aims to isolate the causal effect of the da Vinci system from other confounding factors.

Test for parallel trend with Event Study

Since both hospital department fixed effects and time fixed effects are included in the regressions, our empirical strategy essentially follows a generalized difference-in-differences model. To ensure that the trends in the outcomes between the treated and control groups are parallel before the usage of the da Vinci Surgical System, we employ an event study approach. Following Jacobson et al. (1993) and He and Wang (2017), we estimate the following equation:

$$Y_{ijt} = \alpha_{ij} + \delta_t + \beta_k \times \sum_{k=24}^{k\leq -12,\, k\neq 1} D_{ijt}^{k} + \epsilon_{ijt}$$

Our outcome variables Y_{ijt} is a mix of payment variables for hospital i in department j at time t. Y_{ijt} includes monthly total revenue, revenue from self-pay to nursing revenues.

The dummy variable D_{ijt} jointly represent the da Vinci first-time using event, define s_i as the year when hospital department first install the da Vinci robotic system. We define $D_{ijt}^{-12} = 1 \text{ if } t - s_i \leq -12$ and 0 otherwise. In the baseline model we control fixed effects α_{ij} at the hospital level i department j and time fixed effect δ_t. Standard errors are clustered at hospital department level.

Baseline results

Table 2 reports the results of the Monthly DID regression analysis. The results indicate that the first-time usage of the da Vinci system is associated with a significant reduction in the average length of stay, with a coefficient for first_proc of -1.181, significant at the 5% level. This suggests that patients spend approximately one day less in the hospital after the initial use of the da Vinci system, reflecting increased efficiency and effectiveness of robotic-assisted surgical procedures. On the log form of average length of stay we found a 5% level significant reduction of -0.066%. Continue on patient outcome, we found that the impact on mortality rate is not statistically significant, as the coefficient is close to zero. This finding aligns with the surgeon's qualitative insights that the da Vinci system does not significantly alter patient risk in terms of mortality.

Regarding departmental revenue, we found significant increase of 1.385 on self-pay revenue, this is likely due to China insurance policy does not cover high-end technology surgery. Beside the da Vinci, Patient can choose to conduct laparoscopic surgery for about ¥ 5,000 which are covered by insurance. However, conducting the da Vinci system means that the patients have to pay 100% of ¥30,000. We do not observe significant effects from the first-time use of the da Vinci system on other department outcome, total revenue (0.099), nursing revenue (-0.196). However, there is a significant decrease in per person nursing revenue (-0.1955, significant at the 1% level), suggesting that patients incur lower nursing costs due to shorter hospital stays.

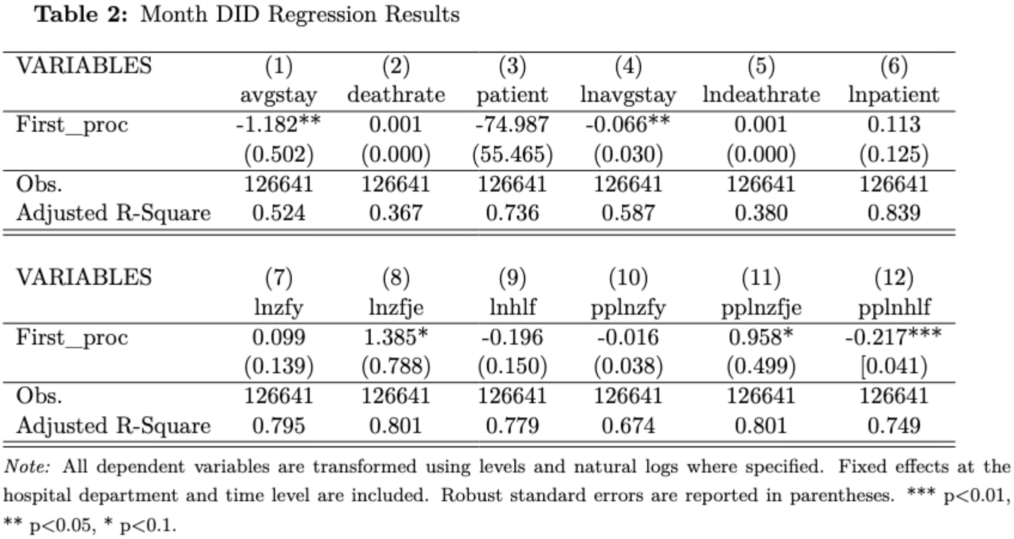

Table 2: Month DID Regression Results

VARIABLES	(1) avgstay	(2) deathrate	(3) patient	(4) lnavgstay	(5) lndeathrate	(6) lnpatient
First_proc	-1.182**	0.001	-74.987	-0.066**	0.001	0.113
	(0.502)	(0.000)	(55.465)	(0.030)	(0.000)	(0.125)
Obs.	126641	126641	126641	126641	126641	126641
Adjusted R-Square	0.524	0.367	0.736	0.587	0.380	0.839

VARIABLES	(7) lnzfy	(8) lnzfje	(9) lnhlf	(10) pplnzfy	(11) pplnzfje	(12) pplnhlf
First_proc	0.099	1.385*	-0.196	-0.016	0.958*	-0.217***
	(0.139)	(0.788)	(0.150)	(0.038)	(0.499)	[0.041)
Obs.	126641	126641	126641	126641	126641	126641
Adjusted R-Square	0.795	0.801	0.779	0.674	0.801	0.749

Note: All dependent variables are transformed using levels and natural logs where specified. Fixed effects at the hospital department and time level are included. Robust standard errors are reported in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Event Study Results

Figure 4 visualize the dynamic effects by displaying the point estimates of self-pay revenue on department level, along with their 95\% confidence intervals. Each point represents an estimated coefficient of the treatment dummy variable for a different number of weeks or months before or after the event. Notably, out-of-pocket revenue exhibits a strong increasing trend starting from month 7, indicating a substantial positive impact of the da Vinci system on patient expenses. Nursing revenue on the second graph display a negative trend starting from month 6, with significance at the 5% level by month 12 and beyond.

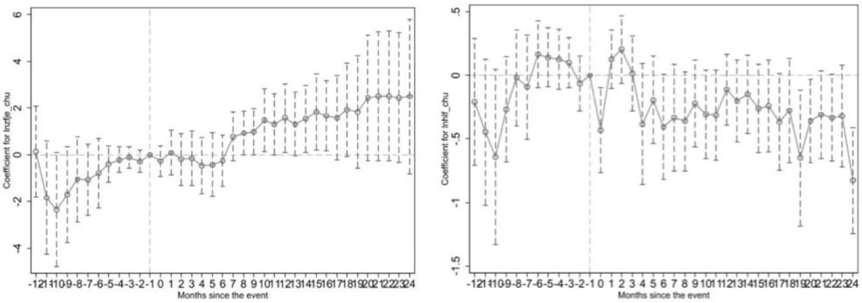

FIGURE 4. EVENT STUDY FOR SELF-PAY REVENUE AND NURSING REVENUE

Robustness Checks

For robustness check we conducted studies with Event DD and Stagger DID and did not find conflict coefficients.

Heterogeneity

We conducted additional DID regression and Event Study using each department data only. We choose departments that have a high amount of da Vinci machines, which include Cardiac, General Surgery, Gynecology, Thoracic, to Urology. We also filter the data to focus on department with more elderly patients and the youngest patients. Lastly, we split gender in order to see the effect of using da Vinci on different gender.

fully meet the requirements for comparing robotic, laparoscopic, and open surgeries, and are capable of providing high-quality data for the study.

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Health Economics Study of Robots and Laparoscopy for Hepatocellular Carcinoma Resection

By Xiao Liang, Haijing Guan, Junhao Zheng, AND Chenyue Yang *

Background: Compared to laparoscopic liver resection, robotic liver resection can reduce postoperative complication rates and hospital stay, and improve patients' postoperative quality of life. However, the costs of robotic liver resection are relatively high, and there is currently a lack of evidence from China on whether robotic liver resection for hepatocellular carcinoma is cost-effective. Objective: To explore the clinical value and medical costs of robotic liver resection compared to laparoscopic liver resection for hepatocellular carcinoma. Methods: We retrospectively collected data from patients with hepatocellular carcinoma who underwent minimally invasive liver resection by a single medical team at Sir Run Run Shaw Hospital of College of Medicine of Zhejiang University from January 2016 to July 2023. Patients were divided into the study group (robotic liver resection group) and the control group (laparoscopic liver resection group). After propensity score matching, we compared perioperative indicators and medical costs before and after matching and conducted subgroup analyses with surgical difficulty as a covariate to analyze the differences in perioperative outcomes and medical costs between the two surgical methods under different surgical difficulties. Results: A total of 277 patients were included in this study (175 in the laparoscopic liver resection group and 102 in the robotic liver resection group). After controlling for baseline characters using propensity score matching, 162 patients (81 in each group) were included for further analysis. The results showed that the robotic liver resection group had less

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intraoperative bleeding, fewer postoperative complications, a lower conversion to open surgery rate, and better surgical safety compared to the laparoscopic liver resection group. The robotic liver resection group had higher medical costs (¥82,885.3 vs. ¥58,643.8, p<0.001); however, the non-surgical costs of laparoscopic liver resection group is significantly higher costs higher than robotic liver resection group. The subgroup analysis indicates that there was no significant difference in costs between the two surgical methods in high-difficulty liver resections. Conclusion: For patients with hepatocellular carcinoma, robotic liver resection has better surgical safety and higher medical costs compared to laparoscopic liver resection. Simultaneously, robotic liver resection appears to be more cost-effective for patients with high surgical difficulty.

I. Background

Robotic liver resection (RLR), as a new technology, may offer better surgical safety compared to laparoscopic liver resection (LLR), though it tends to be more costly. Therefore, whether using robotic resection for the treatment of hepatocellular carcinoma (HCC) is economically effective remains to be evidenced due to the current lack of related proof.

Currently, there are few reports on the health economics of robotic liver resection both domestically and internationally. A meta-analysis in 2022, which included four relevant studies, showed that the cost of RLR (USD 20,205.92) is significantly higher than that of LLR (USD 15,789.75). Cost is a major factor restricting the implementation of RLR (Ciria et al., 2022). However, with the development of modern medicine, surgery aims not only to cure but also to improve the quality of life. In 2020, Mejia et al. reported on 214 liver resection patients and indicated that, despite the higher costs, RLR resulted in shorter hospital stays compared to LLR, making it a better choice for patients requiring minor liver resections (Mejia et al., 2020). Nonetheless, in 2016, Chinese researchers, based on data from 39 patients undergoing robotic and laparoscopic left lateral liver lobe resection, pointed out that RLR is more expensive than LLR for left lateral liver lobe resection, but there is no statistically significant difference in efficacy and safety (Yin et al., 2016). Therefore, whether RLR can improve quality of life and be cost-effective remains a debate.

The 2023 International Guidelines for Robotic Liver Resection experts pointed out that, compared to LLR, RLR has unique therapeutic value in liver-related diseases, and its cost-effectiveness merits further research (Liu et al., 2023). In disciplines such as urology and colorectal surgery, studies have suggested that robotic surgery is cost-effective or highlighted the cost reductions needed to improve the adoption rate of robots (Simianu et al., 2020; Song et al., 2022).

II. Methods

Conduct real-world research, retrospectively collecting data on inpatients diagnosed with HCC at Sir Run Run Shaw Hospital affiliated with Zhejiang University from January 2016 to July 2023. Patients were divided into RLR and LLR groups based on the type of surgery they underwent. On the basis of descriptive analysis, confounding factors were controlled through propensity score matching (PSM) to explore the net benefits of different treatment methods on treatment outcomes and medical costs, and to conduct an economic evaluation. Subgroup analyses were carried out to explore the robustness of the research results.

Continuous variables with a normal distribution are described as mean ± standard deviation, while those with a skewed distribution are described as median (interquartile range), and categorical variables are described as frequency and percentage. Age, BMI, AFP, INR, ALB, AST, TBIL, Child-Pugh classification, vascular invasion, difficulty of operation, and ASA classification were included as covariates in the model for fitting, and propensity scores were calculated for nearest neighbor matching. PSM analysis was conducted using SPSS version 25.0. Patients were divided into four subgroups based on IWATE surgical difficulty grading as "Low", "Intermediate", "Advanced", and "Expert" for subgroup analysis. (Figure 1)

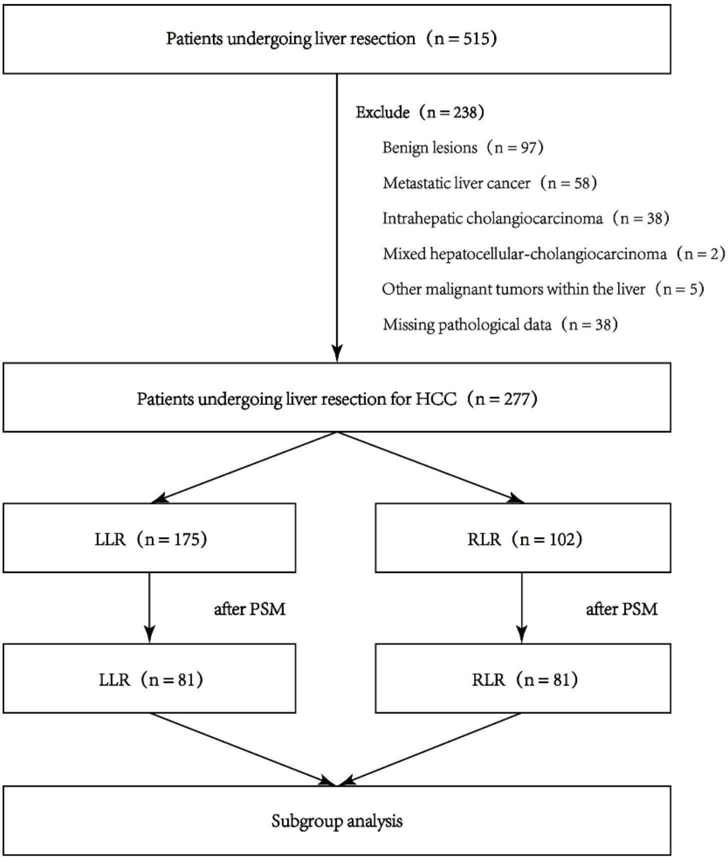

Figure 1. Inclusion And Exclusion Criteria And Flowchart

III. Results

After applying the inclusion and exclusion criteria, a total of 277 patients were included in this study. They were divided into the LLR group (175 patients) and the RLR group (102 patients) based on the surgical method. After PSM, 81 patients in each group were further analyzed and compared.

A. baseline characteristics of the patients

Before PSM, the LLR group had significant differences compared to the RLR group in BMI, AFP, PLT, INR, ALB, AST, liver cirrhosis, Child-Pugh classification, portal hypertension, and IWATE surgical difficulty classification (all $p < 0.05$). There were no significant differences in the remaining indicators. After balancing the baseline characteristics through PSM, 162 patients (81 in the LLR group and 81 in the RLR group) were included for further analysis, and there were no significant differences in baseline characteristics between the LLR and RLR groups (Table 1).

Table1 — Baseline Characteristics Of The Lllr And Rlr Groups Before And After Psm

Baseline characteristics	before PSM (n=277)			after PSM (n=162)		
	LLR (n = 175)	RLR (n = 102)	p value	LLR (n=81)	RLR (n=81)	p value
Age (SD), year	58.7±12.2	60.6±11.5	0.056	62.9±11.6	61.4±11.2	0.390
BMI (SD), kg/^{m}2	23.2±2.8	24.1±3.6	**0.021**	23.6±3.0	24.0±3.3	0.406
Gender, n(%)			0.309			0.678
Female	23 (13.1)	18(17.6)		13(16.0)	15(18.5)	
Male	152 (86.9)	84(82.4)		68(84.0)	66(81.5)	
Tumor size (IQR), cm	2.6 (1.8-4.3)	3.0 (2.2-4.5)	0.163	2.5 (1.8-4.4)	3.2 (2.2-4.7)	0.082
AFP (IQR), ng/mL	17.2 (3.4-277.5)	6.6 (2.5-110.2)	**0.048**	10.2 (3.2-139.8)	6.6 (2.6-110.2)	0.403
PLT (IQR), ×10^{9}/L	126.0 (89.0-172.0)	143.5 (111.0-191.2)	**0.005**	124.0 (95.5-170.0)	138.0 (108.0-190.0)	0.050
PT (IQR), s	13.8 (13.1-14.6)	13.5 (13.0-14.2)	0.068	13.5 (12.9-14.1)	13.5 (13.1-14.2)	0.437
INR (IQR)	1.0 (1.0-1.2)	1.0 (1.0-1.1)	<0. 001	1.0 (1.0-1.1)	1.0 (1.0-1.0)	0.307
TBIL (IQR), μmol/L	14.9 (11.1-21.1)	14.8 (11.2-19.1)	0.728	14.2 (9.6-21.3)	15.3 (11.4-18.8)	0.589
ALB (SD), g/L	39.4±4.8	40.9±4..5	**0.013**	40.2±4.4	40.0±3.6	0.794
AST (IQR), U/L	27.0 (18.0-40.0)	30.0 (23.8-38.0)	**0.026**	25.0 (17.0-41.0)	29.0 (23.5-38.0)	0.100
ALT (IQR), U/L	29.0 (22.0-39.0)	27.0 (19.0-42.3)	0.364	29.0 (21.5-39.0)	27.0 (19.0-41.5)	0.559
Number of tumors, n(%)			0.819			0.658

Single	151(86.3)	87(85.3)		68(84.0)	70(86.4)	
Multiple	24(13.7)	15(14.7)		13(16.0)	11(13.6)	
Liver cirrhosis, n(%)	96(54.8)	41(40.2)	**0.016**	38(46.9)	32(39.5)	0.341
Child-Pugh classification, n(%)			0.049			1
A	159(90.9)	99(93.1)		78(96.3)	78(96.3)	
B or C	16(9.1)	3(2.9)		3(3.7)	3(3.7)	
Portal hypertension, n(%)	11(6.2)	0(0)	**0.028**	5(6.2)	0(0.0)	0.074
History of liver resection, n(%)	22(12.6)	14(13.7)	0.844	12(14.8)	12(14.8)	1
History of laparotomy, n(%)	56(32.0)	35(34.3)	0.693	27(33.3)	31(38.3)	0.512
History of neoadjuvant therapy, n(%)	25(14.2)	10(9.8)	0.279	6(7.4)	9(11.1)	0.416
IWATE tumor location (IQR)	5.0 (3.0-5.0)	5.0 (3.0-5.0)	0.949	5.0 (3.0-5.0)	5.0 (3.0-5.0)	0.576
IWATE tumor size (IQR)	0.0 (0.0-1.0)	1.0 (0.0-1.0)	0.179	0.0 (0.0-1.0)	1.0(0.0-1.0)	0.140
IWATE the extent of liver resection (IQR)	0.0 (0.0-4.0)	3.0 (0.0-4.0)	0.195	0.0 (0.0-4.0)	0.0 (0.0-4.0)	0.946
IWATE proximity to a major vessel (IQR)	0.0 (0.0-0.0)	0.0(0.0-0.0)	0.541	0.0 (0.0-0.0)	0.0 (0.0-0.0)	0.135
IWATE liver function (IQR)	0.0 (0.0-0.0)	0.0 (0.0-0.0)	**0.049**	0.0 (0.0-0.0)	0.0 (0.0-0.0)	0.988
IWATE HALS/hybrid (IQR)	0.0 (0.0-0.0)	0.0 (0.0-0.0)	1	0.0 (0.0-0.0)	0.0 (0.0-0.0)	1
IWATE total score (IQR)	6.0 (5.0-9.0)	7.0 (5.0-9.0)	0.176	6.0 (4.0-9.0)	6.0 (4.5-9.0)	0.57
IWATE difficulty level, n(%)			0.003			0.916
Low	27(15.4)	19(18.6)		16(19.8)	16(19.8)	
Intermediate	82(46.9)	28(27.5)		29(35.8)	25(30.9)	
Advanced	31(17.7)	35(34.3)		21(25.9)	23(28.4)	
Expert	35(20.0)	20(19.6)		15(18.5)	17(21.0)	
ASA classification, n(%)			0.206			0.692
I	8(4.6)	1(1.0)		2(2.5)	1(1.2)	
II	155(88.6)	94(92.2)		72(88.9)	75(92.6)	
III	12(6.9)	7(6.9)		7(8.6)	5(6.2)	
IV~VI	0(0.0)	0(0.0)		0(0.0)	0(0.0)	

Type of medical insurance, n(%)			0.074			0.070
Basic medical insurance for urban workers	164(93.7)	101(99.0)		74(91.4)	80(98.8)	
The others	11(6.3)	1(1.0)		7(8.6)	1(1.2)	
Place of residence, n(%)			0.803			0.727
Local	47(26.9)	26(25.5)		24(29.6)	22(27.2)	
Nonlocal	128(73.1)	76(74.5)		57(70.4)	59(72.8)	

B. clinical outcomes of the patients

Before PSM, the LLR group had significantly higher intraoperative blood loss (100.0 ml vs. 50.0 ml, $p < 0.001$), intraoperative transfusion rate (33 [18.8%] vs. 10 [9.8%], $p = 0.045$), postoperative complication rate (35 [20.0%] vs. 7 [6.8%], $p = 0.003$), conversion to open surgery rate (20 [11.4%] vs. 0 [0.0%], $p = 0.001$), postoperative hospital stay (6.0 days vs. 5.0 days, $p = 0.001$), and total hospital stay (13.0 days vs. 9.5 days, $p = 0.001$) compared to the RLR group, with no significant differences in the remaining indicators (all $p \geq 0.05$).

After balancing baseline characteristics through PSM, a total of 162 patients (81 in the LLR group and 81 in the RLR group) were included in the study. The LLR group still had significantly higher intraoperative blood loss (100.0 ml vs. 50.0 ml, $p = 0.002$), postoperative complication rate (16 [19.8%] vs. 7 [8.6%], $p = 0.043$), postoperative hospital stay (6.0 days vs. 5.0 days, $p = 0.005$), and total hospital stay (12.0 days vs. 10.0 days, $p < 0.001$) compared to the RLR group, with no significant differences in the remaining indicators (all $p \geq 0.05$) (Table 2).

Table2 — Outcomes Of The Llr And Rlr Groups Before And After Psm

Outcomes	before PSM (n=277)			after PSM (n=162)		
	LLR (n = 175)	RLR (n = 102)	p value	LLR (n=81)	RLR (n=81)	p value
Operation time (IQR), min	168.0 (125.0-240.0)	165.0 (110.0-220.0)	0.263	180.0(120.0-250.0)	160.0 (107.5-220.0)	0.134
Status of surgical margins, n(%)			0.464			1
R0	172(98.3)	98(96.1)		80(98.8)	79(97.5)	
R1 or R2	3(1.7)	4(3.9)		1(1.2)	2(2.5)	

Intraoperative blood loss (IQR), mL	100.0 (50.0-400.0)	50.0 (50.0-112.5)	**<0.001**	100.0(50.0-275.0)	50.0 (50.0-125.0)	**0.002**
Intraoperative blood transfusion, n(%)	33(18.8)	10(9.8)	**0.045**	12(14.8)	8(9.8)	0.339
Postoperative complications, n(%)	35(20.0)	7(6.8)	**0.003**	16(19.8)	7(8.6)	**0.043**
ClavienDindo classfication, n(%)			**0.006**			0.062
No	140(80.0)	95(93.1)		65(80.2)	74(91.4)	
I or II	25(14.3)	6(5.9)		10(12.3)	6(7.4)	
III or IV or V	10(5.7)	1(1.0)		6(7.4)	1(1.2)	
Conversion to open surgery during operation, n(%)	20(11.4)	0(0.0)	**0.001**	5(6.2)	0(0.0)	0.069
Reoperation during hospitalization, n(%)	0(0.0)	0(0.0)	/	0(0.0)	0(0.0)	/
Perioperative mortality, n(%)	0(0.0)	0(0.0)	/	0(0.0)	0(0.0)	/
Postoperative hospital stay (IQR), day	6.0(4.0-7.0)	5.0(3.8-6.2)	**0.001**	6.0(4.0-7.0)	5.0(3.5-6.0)	**0.005**
Readmission within 30 days postoperatively due to complications, n(%)	3(1.7)	1(1.0)	1	2(2.5)	1(1.2)	1
Total hospital stay (IQR), day	13.0 (10.0-16.0)	9.5(7.0-13.0)	**<0.001**	12.0 (10.0-16.0)	10.0(8.0-12.0)	**<0.001**
Total hospitalization cost (IQR), ¥	57150.9 (44313.0-76302.3)	81432.5 (74644.9-90934.2)	**<0.001**	58643.8 (45171.2-75899.8)	82885.3 (75617.3-90501.2)	**<0.001**
Out-of-pocket cost (IQR), ¥	16875.0 (9911.2-23013.9)	50333.4 (46274.6-57632.8)	**<0.001**	15972.7 (8999.7-23056.8)	50706.2 (46796.8-57640.6)	**<0.001**
Drug cost (IQR), ¥	15879.4 (11219.3-23459.2)	9955.6 (7687.4-14007.0)	**<0.001**	16517.6 (11994.0-24028.5)	9975.0 (7861.8-14117.4)	**<0.001**
Surgical cost (IQR), ¥	6916.0 (6302.0-7834.3)	43424.9 (42808.6-43897.9)	**<0.001**	6616.0 (6165.0-7481.4)	43424.9 (42754.1-43994.5)	**<0.001**
Examination cost (IQR), ¥	1260.0 (930.0-2153.0)	1160.0 (673.0-1752.8)	**0.010**	1365.0 (1075.0-2340.0)	1115.0 (659.0-1602.0)	**0.001**
Nursing cost (IQR), ¥	1164.0 (879.0-1521.0)	989.6 (784.0-1291.3)	**0.004**	1174.0 (832.5-1555.0)	988.6 (779.9-1255.1)	**0.012**
Consumables cost (IQR), ¥	21113.4 (15486.0-31411.4)	12094.4 (10839.8-18034.8)	**<0.001**	21565.4 (15899.2-32842.0)	12069.4 (10898.8-19094.2)	**<0.001**
Other cost (IQR), ¥	386.0 (182.0-722.0)	486.5 (246.5-851.8)	0.054	341.0(182.0-683.4)	535.0 (276.5-863.0)	**0.004**

C. cost outcomes of the patients

Before PSM, the LLR group had significantly lower total hospitalization cost (57,150.9 ¥ vs. 81,432.5¥, p < 0.001), out-of-pocket cost (16,875.0 ¥ vs. 50,333.4 ¥, p < 0.001), and surgical cost (6,916.0 ¥ vs. 43,424.9 ¥, p < 0.001) compared to the RLR group. However, the LLR group had significantly higher medication cost (15,879.4 ¥ vs. 9,955.6 ¥, p < 0.001), examination cost (1,260.0 ¥ vs. 1,160.0 ¥, p = 0.010), nursing cost (1,164.0 ¥ vs. 989.6 ¥, p = 0.001), and consumable cost (21,113.4 ¥ vs. 12,094.4 ¥, p < 0.001).

After balancing baseline characteristics through PSM, a total of 162 patients (81 in the LLR group and 81 in the RLR group) were included in the study. The LLR group still had significantly lower total total hospitalization cost (58,643.8 ¥ vs. 82,885.3 ¥, p < 0.001), out-of-pocket expense (15,972.7 ¥ vs. 50,706.2 ¥, p < 0.001), surgical cost (6,616.0 ¥ vs. 43,424.9 ¥, p < 0.001), and other cost (341.0 ¥ vs. 535.0 ¥, p = 0.004) compared to the RLR group. However, the LLR group had significantly higher medication cost (16,517.6 ¥ vs. 9,975.0 ¥, p < 0.001), examination cost (1,365.0 ¥ vs. 1,115.0 ¥, p = 0.010), nursing cost (1,174.0 ¥ vs. 988.6 ¥, p = 0.001), and consumable cost (21,565.4 ¥ vs. 12,069.4 ¥, p < 0.001) compared to the RLR group (Table 2).

D. outcomes of subgroup analysis

Subgroup analysis using the IWATE surgical difficulty classification as a covariate showed that in the "Low," "Intermediate," and "Advanced" subgroups, the total hospitalization cost for the LLR group were significantly lower than those for the RLR group (Low: 46,125.7 ¥ vs. 76,647.9 ¥, p < 0.001; Intermediate: 52,692.8 ¥ vs. 76,428.8 ¥, p = 0.003; Advanced: 67,548.3 ¥ vs. 84,725.0 ¥, p = 0.001). However, in the "Expert" group, there was no significant difference in total hospitalization cost between the LLR and RLR groups (75,709.0 ¥ vs. 88,292.6 ¥, p = 0.325) (Figure 2).

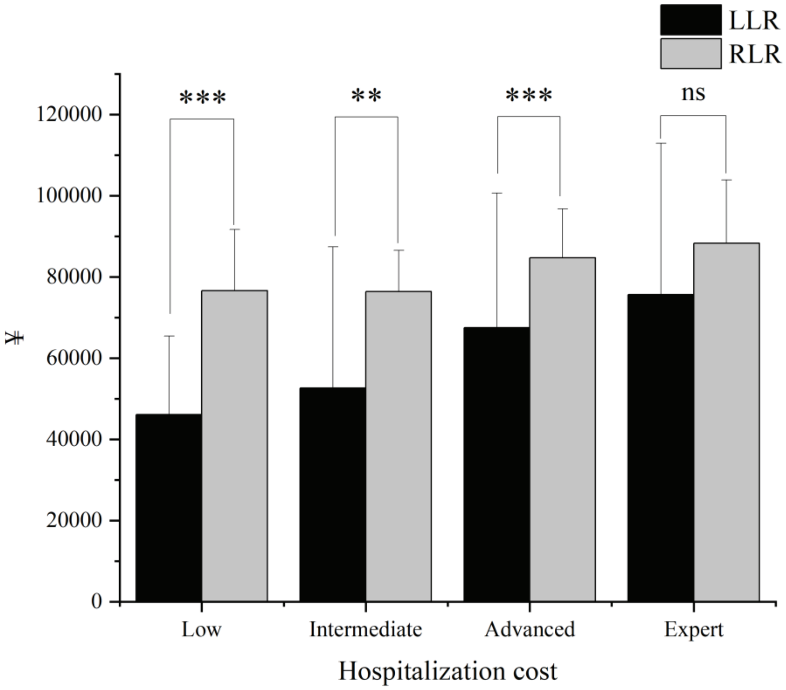

Figure2. Subgroup Analysis Of Total Hospitalization Cost Based On Surgical Difeiculty

***: p＜0.001

**: p＜0.005

ns: p＞0.05

Combining patients with "Low" and "Intermediate" IWATE surgical ratings into a low surgical difficulty group, and those with "Advanced" and "Expert " IWATE surgical ratings into a high surgical difficulty group, a subgroup analysis was performed. The results showed that in both surgical difficulty subgroups, the LLR group had significantly higher intraoperative blood loss (low surgical difficulty: 100.0 (50.0-200.0) vs. 50.0 (20.0-150.0) mL, p=0.013; high surgical difficulty: 200.0 (80.0-400.0) vs. 100.0 (50.0-137.5) mL, p=0.024), longer postoperative hospital stay (low surgical difficulty: 5.0 (4.0-7.0) vs. 4.0 (3.0-5.5) days, p=0.010; high surgical difficulty: 6.5 (5.0-9.0) vs. 5.0 (4.0-7.0) days, p=0.046), and longer LOS (low surgical difficulty: 12.0 (9.0-16.0) vs. 10.0 (7.0-12.0) days, p=0.005; high surgical difficulty: 13.5 (10.0-16.0) vs. 9.5 (8.0-12.0) days, p<0.001) compared to the RLR group. There were no significant differences between the LLR and RLR groups in other outcome indicators in either surgical difficulty subgroup. (Table 3)

Tabble 3 — Analysis Of Clinical Outcome Indicators For Iwate Surgical Difficulty Subgroups

Outcomes	Low + Intermediate (n = 86)			Advanced + Expert (n = 76)		
	LLR (n = 45)	RLR (n = 41)	p value	LLR (n=36)	RLR (n=40)	p value
Operation time (IQR), min	155.0 (100.0-223.8)	120.0 (85.0-180.0)	0.228	195.0 (164.0-260.0)	187.5 (150.0-240.0)	0.265
Status of surgical margins, n(%)			/			1
R0	45(100.0)	41(100.0)		35(97.2)	38(95.0)	
R1 or R2	0(0.0)	0(0.0)		1(2.8)	2(5.0)	
Intraoperative blood loss (IQR), mL	100.0 (50.0-200.0)	50.0 (20.0-150.0)	**0.013**	200.0 (80.0-400.0)	100.0 (50.0-137.5)	**0.024**
Intraoperative blood transfusion, n(%)	7(15.6)	3(7.3)	0.393	5(13.8)	5(12.5)	1
Postoperative complications, n(%)	8(17.8)	3(7.3)	0.147	8(22.2)	4(10.0)	0.145
ClavienDindo classfication, n(%)			0.063			0.341
No	37(82.2)	38(92.7)		28(78.8)	36(90.0)	
I or II	4(8.9)	3(7.3)		6(16.7)	3(7.5)	
III or IV or V	4(8.9)	0(0.0)		2(5.6)	1(2.5)	
Conversion to open surgery during operation, n(%)	3(6.7)	0(0.0)	0.274	2(5.6)	0(0.0)	0.428
Reoperation during hospitalization, n(%)	0(0.0)	0(0.0)	/	0(0.0)	0(0.0)	/
Perioperative mortality, n(%)	0(0.0)	0(0.0)	/	0(0.0)	0(0.0)	/
Postoperative hospital stay (IQR), day	5.0 (4.0-7.0)	4.0(3.0-5.5)	**0.010**	6.5(5.0-9.0)	5.0(4.0-7.0)	**0.046**
Readmission within 30 days postoperatively due to complications, n(%)	2(4.4)	1(2.4)	1	0(0.0)	0(0.0)	/
LOS (IQR), day	12.0 (9.0-16.0)	10.0 (7.0-12.0)	**0.005**	13.5 (10.0-16.0)	9.5 (8.0-12.0)	**<0.001**

IV. Conclusion

For patients with hepatocellular carcinoma, robotic liver resection has better surgical safety and higher medical costs compared to laparoscopic liver resection. Simultaneously, robotic liver resection appears to be more cost-effective for patients with high surgical difficulty.

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Evaluation of Clinical Effectiveness and Health Economics of Robot-Assisted Total Knee Arthroplasty Based on Real-World Data: Progress Report

By BEINI LYU, YANG SONG AND YIXIN ZHOU*

Knee joint disease imposes a substantial health burden in China, with total knee arthroplasty (TKA) being the most effective treatment for end-stage knee osteoarthritis. Compared to traditional surgery, robot-assisted knee arthroplasty (RA-TKA) offers improved precision, alignment consistency, reduced postoperative pain, and faster recovery, which may enhance patient outcomes. However, RA-TKA incurs higher costs than conventional TKA, necessitating a thorough health economic evaluation to determine its cost-effectiveness. After initial data cleaning, this study included 281 patients who underwent RA-TKA and matched them with 281 patients who received conventional TKA based on age, sex, surgery date, and side. Preliminary follow-up for 43 patients in each group revealed that, compared to conventional TKA, RA-TKA had a significantly longer operation time (97.56 minutes vs. 79.05 minutes, p<0.001) but less intraoperative drainage (1.42% vs. 9.25%, p<0.001). While RA-TKA may show a potential advantage in improving joint function and quality of life, these findings are not yet conclusive. Notably, costs during hospitalization were significantly higher for RA-TKA compared to conventional TKA. Continued follow-up will further clarify the differences in clinical outcomes, joint function, quality of life, and hospitalization costs between the two groups.

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I.Introduction

Total joint replacement is the most effective treatment for end-stage hip and knee osteoarthritis, addressing joint deformity, pain, and limited mobility to improve patients' quality of life (Kim et al., 2020). Robot-assisted surgery is a pioneering development in the field of joint arthroplasty, providing advantages such as improved positioning accuracy, precise bone cutting, and customized prosthesis placement. Prior studies have shown that, compared to traditional total knee arthroplasty (TKA), robot-assisted knee arthroplasty (RA-TKA) offers benefits such as accurate bone resection, individualized prosthesis placement, better preservation of periarticular soft tissue, and reduced use of analgesics. However, it also tends to require longer surgical time (Shao et al., 2023; Subramanian et al., 2019; Yang et al., 2024).

Since 2012, policies at various government levels have encouraged the development and application of surgical robotics. The "Guiding Opinions on Promoting the Healthy Development of the Pharmaceutical Industry" (2016) advocated for technological innovation in medical devices, including surgical robots. In January 2024, the Ministry of Industry and Information Technology and 17 other departments released the "Implementation Plan of the 'Robot+' Application Action," aiming to accelerate technological breakthroughs in robotics across multiple fields. The rapid development of orthopaedic surgical robots requires balancing socio-economic considerations to guide their rational advancement. Accurately assessing the clinical and economic value of surgical robots and setting appropriate payment standards are crucial for supporting both the development of robotic surgery and relevant policy-making.

Using real-world data from patients undergoing TKA, this study aimed to compare the clinical outcomes, quality of life, and in-hospital medical costs between RA-TKA and conventional TKA, with the goal of clarifying the cost-effectiveness of RA-TKA.

II. Methods

This retrospective cohort study included patients aged 21-80 years with American Society of Anaesthesiologists (ASA I-II) scores who received RA-TKA or conventional TKA for osteoarthritis or joint deformity at Jishuitan Hospital's Orthopedic Department between July 2020 and March 2024. Exclusion criteria included pregnancy, knee revision surgery, severe knee deformities (flexion >20° or varus/valgus >20°), rheumatoid arthritis, or infectious arthritis.

Demographic and clinical data, including age, sex, surgical indications, preoperative comorbidities, operation time, intraoperative blood loss and drainage, and postoperative complications, were collected from electronic medical records. In-hospitalization medical costs, including total hospital expenses, surgical fees, examination fees, consumables, laboratory fees, drug costs, and other expenses, were also recorded.

Patients were followed up by healthcare staff via telephone to assess joint function and quality of life. Joint function was evaluated using the Western Ontario and McMaster Universities Arthritis Index (WOMAC), and quality of life was assessed using the EQ-5D-5L questionnaire, based on the established utility score system for the Chinese population (Liu et al., 2014). Information on prosthesis revision, loosening, and joint-related visits was also collected during follow-up.

Statistical Analysis. Continuous variables were presented as mean (standard deviation) or median (interquartile range), and categorical variables as frequency (percentage). T-tests or chi-square tests were used to compare the characteristics of patients in the RA-TKA and conventional TKA groups. A two-sided p-value <0.05 was considered statistically significant.

III.Preliminary results

After data cleaning, 281 patients who underwent RA-TKA were matched 1:1 by age (±3 years), sex, surgery date (±60 days), and surgical side with 281 patients who received conventional TKA. Age and sex distributions were nearly identical between the groups (mean age of RA-TKA group: 67.33 [6.86] years; conventional TKA group: 67.38 [6.51] years, Table 1). All patients were diagnosed with osteoarthritis, and 52.67% underwent left-sided knee replacement. There were no significant differences between the two groups in body mass index (BMI), cardiovascular disease, diabetes, or ASA scores (all p>0.05).

Significant differences were observed in surgical parameters between the two groups. The average operation time for RA-TKA was 97.56 (21.25) minutes, compared to 79.05 (19.54) minutes for conventional TKA (p<0.001). Regarding intraoperative drainage, most patients had minimal drainage; therefore, the presence or absence of drainage was used as an outcome measure. A significantly lower proportion of RA-TKA patients had intraoperative drainage compared to conventional TKA patients (1.42% vs. 9.25%, p<0.001). No significant differences were found in intraoperative blood loss between the groups.

Based on telephone follow-ups for 43 matched pairs, the median follow-up time was 15.01 (9.78, 22.35) months, with no significant difference between groups (Table 2).

No cases of prosthesis revision, loosening, or infection were observed in either group. One patient in the RA-TKA group experienced joint-related rehospitalization and surgery post-discharge, while no related events were observed in the conventional group. In terms of outpatient visits, three cases (6.98%) were observed in the RA-TKA group, compared to two cases (4.65%) in the conventional TKA group.

No significant differences in joint function or quality of life measures were found between the groups at follow-up, including patient satisfaction, WOMAC scores, EQ-5D health scores, and quality-adjusted life years (QALYs) (Table 3). Although the RA-TKA group showed greater improvements in WOMAC scores and overall EQ-5D-5L health scores, these differences were not statistically significant.

During hospitalization, the RA-TKA group incurred significantly higher costs than the conventional TKA group, with higher total hospital expenses (47,634 CNY vs. 40,750 CNY), surgical fees (10,972 CNY vs. 4,813 CNY), and drug costs (2,905 CNY vs. 2,481 CNY) ($p<0.05$ for all, Table 4). Other expense categories showed no significant differences between the groups.

IV. Preliminary summary

Preliminary data analysis and partial follow-up suggest that RA-TKA may offer advantages in joint function and quality of life improvement over conventional TKA, aligning with patient feedback. However, the limited sample size precludes definitive conclusions. Notably, hospitalization costs for RA-TKA, particularly surgical fees, are significantly higher than those for conventional TKA.

The study will continue to follow up with patients to further clarify the impact of RA-TKA on joint function, quality of life, and medical expenses. Additionally, subgroup analyses will be conducted to explore the effects of RA-TKA versus conventional TKA on these outcomes in patients of different ages and varying levels of joint disease severity.

TABLE 1. PATIENT CHARACTERISTICS IN THE ROBOT-ASSISTED AND CONVENTIONAL SURGERY GROUPS AFTER MATCHING

	Robot-Assisted Group (n=281)	Conventional Surgery Group (n=281)	P value
Age, years	67.33 (6.86)	67.38 (6.51)	0.38
Female	230 (81.85)	230 (81.85)	/
Knee osteoarthritis	281 (100)	281 (100)	/

Surgery year, post-2022	147 (52.31)	142 (50.53)	0.74
Surgery site, left	148 (52.67)	148 (52.67)	/
BMI, kg/m^2	28.94 (10.93)	26.68 (3.86)	0.068
Cardiovascular disease	156 (55.52)	136 48.40)	0.11
Diabetes	50 (17.79)	48 (17.08)	0.91
ASA class 1	93 (33.10)	106 (37.72)	0.33

ASA, American Society of Anesthesiologists. BMI, body mass index.

Table 2. Clinical Outcomes of Patients

	Robot-Assisted Group (n=43)	Conventional Surgery Group (n=43)	P value
Postoperative months	14.90 (9.85, 21.87)	15.13(8.88, 22.43)	0.86
Prosthesis revision	0	0	
Prosthesis loosening	0	0	
Prosthesis infection	0	0	
Joint-related hospitalization	1 (2.33)	0	
Joint-related surgery	1 (2.33)	0	
Joint-related outpatient visits	3 (6.98)	2 (4.65)	0.79

Table 3. Health outcomes of patients

	Robot-Assisted Group (n=43)	Conventional Surgery Group (n=43)	P value
Satisfaction with current knee function, very satisfied	29 (67.44)	30 (69.77)	0.55
WOMAC Score			
Preoperational	53.19 (23.88)	48.56 (22.54)	0.36
Follow-up	5.09 (7.07)	6.79 (11.71)	0.42
Difference	48.09 (22.96)	41.77 (22.08)	0.20
ED-5D-5L Health score			
Preoperational	53.69 (16.12)	55.70 (12.84)	0.53
Follow-up	86.71 (10.49)	86.28 (11.40)	0.86
Difference	33.02 (17.73)	30.58 (14.20)	0.49
QALYs	0.95 (0.47)	0.90 (0.42)	0.63

QALYs, quality-adjusted life years

Table 4.In-hospital medical expenditures

	Robot-Assisted Group (n=43)	Conventional Surgery Group (n=43)	P value
Total hospitalization cost, RMB	39520 (34417,61589)	41329 (28042,51123)	0.15
Surgery	10376 (10376,14409)	4838 (2376, 6409)	<0.001
Examination	674.4 (410.8, 1073.0)	802.9 (314.4, 1574.9)	0.99
Consumable	20596 (14471, 41737)	29025(17140, 39287)	0.50
Laboratory	387 (305, 1257)	1361 (207, 1699)	0.84
Medication	2758 (2109, 3366)	2209 (18157, 2983)	0.026
Others	67 (4, 67)	45 (4, 67)	0.35

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AI and Career Barriers in Surgery Departments: Research Progress

By Yuhang Pan, Junjian Yi AND Qingyuan Zhou *

1. Baseline Results

In this section, we present our main findings, showing the effect of the introduction of da Vinci robots on gender composition in surgical departments.

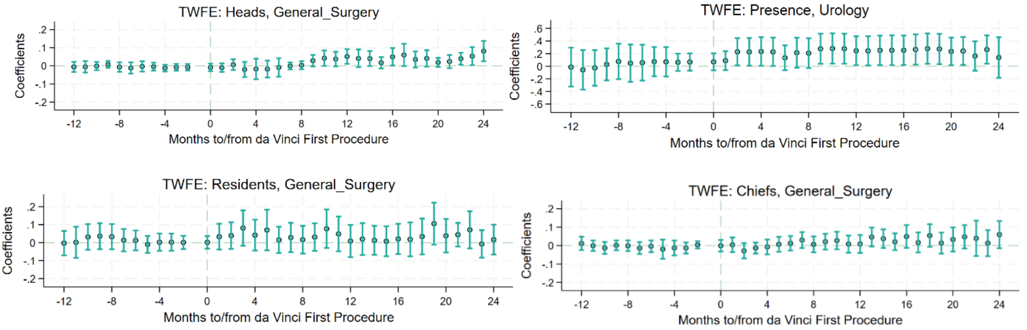

Figure 1. Months to/from da Vinci First Procedure and Female Presence

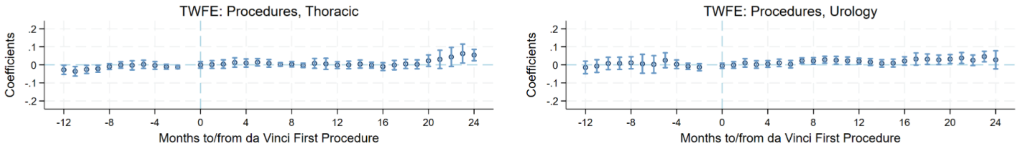

Figure 2. Months to/from da Vinci First Procedure and Female Workloads

Figure 1 depicts the changes in female presence and ratio of female heads, chiefs, residents and attendings across various departments over time. We use the difference between the treated and control hospital-departments one month before the introduction of the robots as the reference group. We find that in the months following the introduction of the da Vinci surgical system, the relative presence of females increases in departments of urology and general surgery, while remaining relatively stable in others. Additionally, in the department of general surgery, proportions of female heads and chiefs increase,

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indicating more promotion opportunities for females. However, these changes do not occur immediately after the adoption of robots, possibly because it takes time to make personnel adjustments.

Figure 2 illustrates trends in female workloads across different departments. It reveals that after the technology adoption, departments of thoracic and urology experience an increase in the volume of procedures performed by female surgeons. This provides evidence that skill-biased technological changes could alter the comparative advantage between males and females and facilitate greater female participation and entry into surgery departments.

2. Work in progress

The evidence in the previous section suggests increasing presence and opportunities for promotion of females in some departments. This section examines mechanisms related to this narrowing gender gap. Specifically, we employ case-level and physician-level data to estimate the impact of da Vinci robot adoption on physicians' decisions concerning resource utilization and patient health outcomes by gender.

2.1 case-level evidence on physician productivity by gender

Outcome Variables. To measure medical resource use, we include two primary outcomes: (i) the patient length of stay (i.e., the date between patient assignment to the provider and patient discharge), (ii) fees spent on tests and exams performed on the patient and (iii) the total cost of care during the current hospital stay. To mitigate the effect of extreme values, we take log of the medical spending. To measure quality of care, we examine two prominent patient outcomes: (i) indicators of patient 30-day inpatient readmission—whether the patient is rehospitalized within 30 days of the discharge and (ii) indicators of patient in-hospital mortality.

Control Variables. Our specification also includes a vector of patient covariates, including indicators for five-year age bins, gender and indicators for three-digit International Classification of Diseases, Tenth revision (ICD-10) codes of patient's primary diagnosis of the visit.

Our empirical specification takes the following form:

$$Y_{ijt} = \sum_{k=-12,\, k\neq -1}^{k=24} \beta_k MR_{jt,k} + X_i\gamma + \delta_j + \eta_t + \epsilon_{jt}\#(1)$$

where the Y_{ijt} denotes measures of medical resource use and quality of care for case i in hospital-department j and month-year t. $MR_{jt,k}$ represents dummy variables that equal 1 if in month-year t, there are months before(after) the first robotic-assisted procedure in hospital-department j, and 0 otherwise. X_i denotes patient risk adjusters. We also include hospital-department fixed effect δ_j and month-year fixed effect η_t. ϵ_{jt} is the idiosyncratic error term. We cluster standard errors by hospital-department.

2.2physician-level evidence on physician productivity by gender

To investigate why female surgeons have more promotion opportunities after the introduction of robots, we assess the extent to which robot adoption alter surgeons' productivity separately for males and females.

We adopt the following specification to estimate the causal effect of the physician's use of robots on his/her productivity and workloads:

$$Y_{it} = \sum_{k=-12,\, k\neq -1}^{k=24} \beta_k MR_{it,k} + \delta_i + \eta_t + \epsilon_{it} \#(2)$$

where subscript i denotes a physician and t denotes the quarter-year. The dependent variable Y_{it} represents in-hospital death rate, 30-day inpatient readmission rate, average hospitalization days and average spendings of physician i's patients as well as total number of procedures of physician i in time t. The independent variables of interest $MR_{it,k}$ are dummy variables that equal 1 if in quarter-year t, there are k quarters before(after) physician i first conduct a surgery using da Vinci robot, and 0 otherwise. We include physician fixed effects δ_i to control for physician heterogeneities. That is, the estimation in equation (2) exploits within-physician variations. Finally, ϵ_{it} is the error term. Standard errors are clustered at physician level.

Does Robotic Surgery Help Reduce the Economic Burden of Malignant Tumors in the Pancreas? A Cost-of-Illness Study

By YIN SHI, ZITING WU*

Abstract: Through a literature review, this study summarizes the main findings and conclusions of existing research regarding the effectiveness of robotic surgery compared to laparoscopic or open surgery for the treatment of pancreatic malignancies, as well as unresolved issues in the field. The primary findings and conclusions are as follows: Laparoscopic surgery demonstrates advantages in perioperative safety compared to open surgery, although the oncological benefits are not clearly superior; robotic surgery shows advantages in perioperative safety over open surgery, with some benefits in oncological outcomes for pancreatic head cancer, while no significant advantage is observed for pancreatic body and tail cancer. The comparison between robotic and laparoscopic surgeries regarding perioperative safety and oncological metrics requires support from large sample studies, and the impact of the learning curve on robotic surgical outcomes must be considered. To validate these claims, broader studies using standardized methods are needed, with an emphasis on large-scale research and long-term outcomes in developing countries. Additionally, the surgeon's learning curve and the subtype of pancreatic malignancies are crucial for a comprehensive assessment of the effectiveness and cost-effectiveness of robotic surgery. We will also provide a detailed report on the statistical analysis methods to be employed in this study and plan to conduct data analysis accordingly after data acquisition.

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I. Background and Objective

Since the first laparoscopic pancreatoduodenectomy (LPD) was reported in 1994, the exploration of the application of laparoscopic or robotic technology in pancreatic surgery has been ongoing (Shah and Singh 2024). Currently, the controversy over the application of laparoscopic or robot-assisted surgery for curative treatment of pancreatic cancer mainly focuses on the oncological evaluation of treatment effects and surgical safety. Regarding laparoscopic or robot-assisted radical surgery for pancreatic cancer, Chinese experts discussed its efficacy and safety in the 2022 consensus, believing that minimally invasive radical surgery has a broad application prospect (Study Group of Minimally Invasive Treatment for Pancreatic Cancer in China Anti-Cancer Association and Chinese Pancreatic Surgery Association 2023), but it is necessary to emphasize a long learning curve (Pancreatic Cancer Committee of Chinese Anti-cancer Association 2021).

This research progress report consists of two parts. First, it includes a literature review evaluating the effectiveness of robotic surgery compared to laparoscopic and open surgery for pancreatic cancer, aiming to supplement the previous findings on cost-effectiveness studies of robotic versus laparoscopic and open surgeries. Second, it provides a detailed account of the statistical analysis methods to be used in this study, with plans to conduct data analysis based on these methods after data acquisition.

II. Methods

A.Literature review

We searched PubMed without language restrictions, using the terms "pancreatic" and "pancreas" in combination with "cancer," "adenocarcinoma," and "carcinoma." We also combined these terms with "robot," "robotic," and "surgery." The most relevant clinical trials, systematic reviews and meta-analyses, other original research articles, and guidelines from January 1, 2011, to May 30, 2024, were included. Two researchers screened and summarized literature on economics and health effects, respectively.

B.Statistical analysis methods

Description of Demographic and Temporal Distribution (for three types of surgeries): The demographic characteristics and time distribution of all participants will be described, categorized by the three surgical approaches.

Cost Discounting Not Required Due to Study Timeframe: Since the study duration does not exceed one year, there is no need for cost discounting. For retrospective data involving past expenses, to account for inflation or deflation, the costs will be converted to 2023 values using the Consumer Price Index (CPI) [Data source: National Bureau of Statistics, https://data.stats.gov.cn/search.htm?s=CPI].

Sample of 240 Participants for Initial Modeling: A sample of 240 participants will be extracted, and their demographic characteristics and time distribution will be described across the three surgical approaches.

Predictive Models for Unobservable Costs Based on Initial Sample: First, predictive models for various unobservable costs will be constructed using data from the 240 participants, then extrapolated to the entire sample. During the study period, direct medical costs, direct non-medical costs, and indirect costs will be collected for all participants within 30 days post-discharge.

（1）Cox regression model will be used to assess the relationship between post-discharge survival and its influencing factors for patients with pancreatic malignancies. The Lasso method will be used to estimate the coefficients of the Cox regression model, reducing the risk of overfitting due to high-dimensional and complex data. Lasso regression shrinks some insignificant coefficients to zero, enhancing model interpretability and predictive power. The specific model is as follows:

$$\lambda(t) = \lambda_0(t)\exp^{\beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n}$$

Where $\lambda(t)$ is the hazard function at time t(in days),$\lambda_0(t)$is the baseline hazard function representing the average risk, and $\beta_1 \sim \beta_n$ are the regression coefficients for covariates $x_1 \sim x_n$, which include gender, age, ethnicity, type of medical insurance, marital status, residential location (urban/rural), clinical stage, age-adjusted Charlson comorbidity index, surgical approach (robotic/laparoscopic/open), operation duration, intraoperative blood loss, and surgeon's experience (number of surgeries previously performed).

（2）The model will predict the survival time t for each individual (in days).

（3）Based on the survival model, predictive models for direct non-medical costs and indirect costs will be constructed as follows:

$$\mathrm{Cost}_{\mathrm{non-med-in}hosp} = \mathrm{Cost}_{\mathrm{med}} + \mathrm{x}_1 + \ldots + \mathrm{x}_\mathrm{n} + \mathrm{LOS}$$

$$\mathrm{Cost}_{\mathrm{non-med-out}hosp}/\mathrm{t} = \mathrm{Cost}_{\mathrm{med}} + \mathrm{x}_1 + \ldots + \mathrm{x}_\mathrm{n}$$

Where $\mathrm{Cost}_{\mathrm{non-med-in}hosp}$ is the direct non-medical costs during hospitalization; $\mathrm{Cost}_{\mathrm{non-med-outhosp}}/\mathrm{t}$ is the daily direct non-medical costs post-discharge; $\mathrm{x}_1 \sim \mathrm{x}_\mathrm{n}$ is the surgical approach (robotic/laparoscopic/open), gender, age, ethnicity, type of medical insurance, marital status, residential location (urban/county/town/rural), clinical stage, age-adjusted Charlson comorbidity index, operation duration, intraoperative blood loss, and surgeon's experience (number of surgeries previously performed); and LOS is the length of hospital stay.

$$\mathrm{Cost}_{\mathrm{indirect-in}hosp} = \mathrm{Cost}_{\mathrm{med}} + \mathrm{x}_1 + \ldots + \mathrm{x}_\mathrm{n} + \mathrm{LOS}$$

$$\mathrm{Cost}_{\mathrm{indirect-out}hosp} = \mathrm{Cost}_{\mathrm{med}} + \mathrm{x}_1 + \ldots + \mathrm{x}_\mathrm{n}$$

Where $\mathrm{Cost}_{\mathrm{indirect-in}hosp}$ is the indirect costs incurred during hospitalization; $\mathrm{Cost}_{\mathrm{indirect-out}hosp}$ the indirect costs outside the hospital; $\chi 2$ the indirect costs outside the hospital; $\mathrm{x}_1 \sim \mathrm{x}_\mathrm{n}$ is the surgical approach (robotic/laparoscopic/open), gender, age, ethnicity, type of medical insurance, marital status, residential location (urban/county/town/rural), clinical stage, age-adjusted Charlson comorbidity index, operation duration, intraoperative blood loss, and surgeon's experience (number of surgeries previously performed); and is the length of hospital stay.

（4） The constructed predictive models for direct non-medical and indirect costs will be used to estimate cost information for the entire sample during hospitalization and within 30 days post-discharge.

Descriptive Statistics for Quantitative Indicators: For quantitative indicators, the following descriptive statistics will be calculated: count (N), mean, standard deviation (SD), median, minimum (Min), and maximum (Max). The Kruskal-Wallis test will be used for non-normally distributed variables, and the T-test for normally distributed variables. Categorical variables will be presented as numbers and percentages, and compared using the Chi-square test.

Adjustments for Confounding Variables Using Inverse Probability of Treatment Weighting (IPTW): IPTW will be applied to adjust for differences in baseline patient characteristics. This method controls for observable confounders such as demographic, disease-related, and surgeon-related factors.

(1) A logistic regression model will be constructed to predict the likelihood of receiving a particular treatment based on individual characteristics (e.g., socioeconomic status, disease-related indicators, surgeon's characteristics).

(2) Weights will be calculated using the predicted probability P(Treatment | X) from the logistic regression model. For individuals who received the treatment, the weight will be 1/P(Treatment | X).

(3) Weighted regression analysis will be performed using least squares or generalized linear models (GLM), applying the calculated weights wi to estimate causal effects and reduce confounding.

(4) Sensitivity analysis will be conducted to assess the robustness of the results to different model assumptions.

Evaluation of Cost Impact Using Generalized Linear Model (GLM) Based on Gamma Distribution: A GLM based on the Gamma distribution will be used to evaluate the impact of robotic surgery on direct medical costs, non-medical costs, and indirect costs. The model is as follows:

$$\log(\mathrm{Y}) = \beta_0 + \sum_{j=1}^{J} \beta_j \mathrm{comorbidity}_j + \varepsilon$$

Where Y is the direct medical costs, direct non-medical costs, or indirect costs, j denotes the j-th comorbid condition of the patient (where the patient may have from 1 to j comorbid conditions).

$$\mathrm{AF}_j = p_j(e^{\beta_j} - 1)$$

Where AF_j is the proportion of total costs attributed to comorbid condition j, and p_j is the probability of simultaneous occurrence of the target disease and comorbid condition in the sample. When AF_j=0.006, it indicates that 0.6% of the total costs are attributed to comorbid condition j. The total costs attributed to various comorbid conditions will be referred to as "outflow," calculated as follows:

$$\mathrm{outflow} = \text{total expenditure of target disease} * \sum_j \mathrm{AF}_j$$

The costs attributable to pancreatic cancer are calculated as follows:

$$\begin{aligned}&\text{Adjusted total expenditure of target disease}\\&\qquad\qquad= \text{total expenditure of target disease} - \text{outflow}\end{aligned}$$

Using a generalized linear model (GLM), the impact of robotic surgery on cost levels will be assessed, with costs assumed to follow a gamma distribution. $Adjusted\ total\ expenditure_i$ is the costs for individual i, X_i a set of influencing factors, including the surgical approach (robotic/laparoscopic/open), gender, age, ethnicity, type of medical insurance, marital status, residential location (urban/county/town/rural), clinical stage, age-adjusted Charlson comorbidity index, operation duration, intraoperative blood loss, and surgeon's experience (number of surgeries previously performed);and ε_i is the error term.

$$\log(\text{Adjusted total expenditure}_i) = \beta_0 + \beta X_i + \varepsilon_i$$

Subgroup Analysis: Subgroup analyses will be conducted based on different disease types and whether the lead surgeon has surpassed the learning curve, utilizing the generalized linear model from the previous step.

III. Results

A.Evaluation of the effectiveness of robotic surgery compared to laparoscopic and open surgery for pancreatic cancer treatment.

Most existing studies compared the differences in effectiveness between laparoscopic surgery, or minimally invasive surgical approaches mainly involving laparoscopic surgery, and open surgery. In summary, laparoscopic surgery has advantages in perioperative safety but not in oncological benefits. — Laparoscopic surgery for pancreatic head and body-tail cancer has some advantages over open surgery in perioperative safety indicators, but no advantage in postoperative 90-day mortality rate. For pancreatic head and body-tail cancer, the total operating time for LPD is slightly longer than that for open pancreatoduodenectomy (OPD) (Kuesters et al. 2018; Feng et al. 2021; Zhou et al. 2019; Stauffer et al. 2017). LPD has advantages over OPD in terms of hospital stay and intraoperative blood loss, while there is no statistical significance in postoperative complications such as pancreatic fistula, postoperative bleeding, and perioperative mortality rate (Feng et al. 2021; Jiang, Zhang, and Zhou 2019; Yin, Jian, Hou, and Jin 2019). Chapman et al. (Chapman et al. 2018) analyzed the 90-day mortality rate of patients over 75 years old with pancreatic head cancer who underwent LPD and OPD in the National Cancer Database (NCDB) and found that the mortality rate of elderly LPD patients was lower than that of OPD. However, the results of a retrospective study of a large sample of pancreatic body-tail cancer case data in the NCDB suggested that there was no statistical significance in the 90-day mortality rate between LDP and ODP (Kantor et al. 2017).

The oncological benefits of laparoscopic surgery for pancreatic head cancer are unclear, and no oncological benefits were found for the treatment of pancreatic body-tail cancer. For pancreatic head cancer, LPD has advantages over OPD in R0 resection rate, the number of lymph nodes obtained, and the start time of postoperative adjuvant chemotherapy(Jiang, Zhang, and Zhou 2019; Yin, Jian, Hou, and Jin 2019; Feng et al. 2021; Peng et al. 2019); however, another study did not find any differences between LPD and OPD in the aforementioned outcome indicators (Chen et al. 2020). But the difference in the proportion of postoperative adjuvant chemotherapy received by the two surgical methods is not statistically significant (Chen et al. 2020; Peng et al. 2019). Meta-analysis results for long-term survival after LPD for pancreatic head cancer show that the disease-free survival period of LPD is longer than that of OPD(Peng et al. 2019; Chen et al. 2020); however, some literature believes that there is no statistical significance in the overall survival (OS) difference between the two (Feng et al. 2021; Zhou et al. 2019). For pancreatic body-tail cancer, there is no statistical significance in the differences between LDP and ODP in R0 resection rate (Ricci et al. 2015; Riviere et al. 2016; Gavriilidis, Roberts, and Sutcliffe 2018) and the number of lymph nodes removed (Gavriilidis, Roberts, and Sutcliffe 2018; Ricci et al. 2015). In terms of long-term survival, there is no statistical significance in the differences in chemotherapy completion rate, postoperative recurrence rate, and overall survival after patients with cancer undergo LDP or ODP (Ricci et al. 2015).

Limited studies have compared the differences between robotic and open surgery and found that robotic surgery has advantages in perioperative safety, but in terms of oncological indicators, robotic surgery for pancreatic head cancer has certain advantages, while there is no obvious advantage for pancreatic body-tail cancer. — Robotic surgery for pancreatic head and body-tail cancer has some advantages over open surgery in perioperative safety indicators. A multicenter randomized controlled trial based on the Chinese population showed that robotic surgery was superior to open surgery in reducing hospital stay (Liu et al. 2024). Vining et al. (Vining et al. 2020) conducted a Propensity Score-Matched (PSM) analysis of pancreatic head cancer data in the American College of Surgeons-National Surgical Quality Improvement Program (ACS-NSQIP), and the results showed that the incidence of postoperative bleeding in the RPD group was lower than that in the OPD group, while there was no statistical significance in postoperative pancreatic fistula. Two other single-center small sample PSM studies also reached similar conclusions (Kauffmann et al. 2019; Baimas-George et al. 2020). Nassour et al. (Nassour et al. 2020) included 332 and 2,386 patients with pancreatic body-tail cancer treated with RDP and ODP respectively in their study, and the results showed that RDP was superior to ODP in terms of hospital stay and 90-day mortality rate.

Some oncological indicators of robotic surgery for pancreatic head cancer are better than those of open surgery, and the oncological advantages of robotic surgery for pancreatic body-tail cancer are still controversial. Nassour et al. (Nassour et al. 2020) analyzed the data in the NCDB and found that the number of lymph nodes obtained and the rate of postoperative adjuvant chemotherapy in the RPD group were better than those in the OPD group, while there was no statistical significance in R0 resection rate and postoperative survival. Two single-center PSM analyses also reached similar conclusions (Kauffmann et al. 2019; Baimas-George et al. 2020). Some researchers believe that pancreatic head cancer patients who undergo RPD can receive adjuvant chemotherapy earlier after surgery than those who undergo OPD (Boggi et al. 2016). Some studies show that RDP is superior to ODP in the number of lymph nodes removed and the rate of postoperative adjuvant chemotherapy, while there is no statistical significance in R0 resection rate (Nassour et al. 2020), but some studies did not find any differences between the two in the number of lymph nodes removed and R0 resection rate (Lee et al. 2015).

There are limited investigations into the differences between robotic surgery and laparoscopic surgery. Based on relevant studies, we found that the comparison between robotic surgery and laparoscopic surgery in terms of perioperative safety and oncological indicators needs to be supported by large-sample studies. At the same time, the impact of the learning curve on the effectiveness of robotic surgery should be considered. — The advantages of robotic surgery for pancreatic head and body-tail cancer in perioperative indicators need to be confirmed by large-sample studies. For pancreatic head cancer, a multicenter retrospective study(Zhang et al. 2023) based on a sample population of 2,255 in China showed that robotic surgery helps to shorten operating time, reduce intraoperative blood loss, and conversion rate to open surgery, with no obvious advantages in other indicators. The remaining study results show that the conversion rate to open surgery for RPD is lower than that for LPD (Stiles et al. 2018; Kamarajah et al. 2020), and it can also reduce the rate of intraoperative transfusion (Kamarajah et al. 2020), with no difference in other perioperative safety indicators (Kamarajah et al. 2020; Stiles et al. 2018). However, the results of this study were based on about 20 patients who received RPD, so they only represent the safety data in the early stage of the learning curve. For pancreatic body-tail cancer cases, retrospective analysis found that the conversion rate to open surgery for RDP is lower than that for LDP, but there is no statistical significance in the differences in hospital stay and 90-day mortality rate (Watson et al. 2020; Raoof et al. 2018).

The advantages of oncological indicators for robotic surgery for pancreatic head cancer are not obvious, and most of the oncological indicators for robotic surgery for pancreatic body-tail cancer are not obvious or controversial. There is no statistical significance in the differences between RPD and LPD in R0 resection rate, the number of lymph nodes removed, the rate of postoperative adjuvant chemotherapy, OS, and the survival rates at 1, 2, and 3 years for pancreatic head cancer (Nassour et al. 2020; Wehrle et al. 2024). For pancreatic body-tail cancer, there is no statistical significance in the differences between RDP and LDP in R0 resection rate, the number of lymph nodes obtained, the time of postoperative adjuvant chemotherapy, and the rate of adjuvant chemotherapy (Raoof et al. 2018). Watson et al. (Watson et al. 2020) analyzed the pancreatic body-tail cancer case data in the NCDB, and except for the number of lymph nodes obtained by RDP being better than LDP, there was no advantage in other oncological indicators. From the long-term survival results, except for Watson et al.(Watson et al. 2020) reporting that the OS of RDP is better than LDP, other studies did not find any statistical significance in the differences between the two in OS and the survival rates at 1, 2, and 3 years (Raoof et al. 2018; Baimas-George et al. 2020; Daouadi et al. 2013).

B.Progress on Data Collection

Acquisition of Direct Non-Medical and Indirect Costs through Surveys:

(1)A total of 17 qualified surveys have been collected to date. The collection process is as follows:

(2)Ward nurses at Chinese People's Liberation Army (PLA) General Hospital are responsible for gathering the survey information.

(3)Data collection has begun for pancreatic malignancy patients discharged since September 2, specifically those who underwent pancreatic resection, with a target of 80 cases each for robotic, laparoscopic, and open surgeries.

(4)Either patients or their family members can fill out the surveys.

(5)To ensure the accuracy of the collected information and minimize disruption to patients and clinical operations, the survey questions have been simplified and kept to a minimum in number, following discussions with clinical doctors.

Acquisition of Medical Costs through Institutional Data Recording:

A total of 12,166 cases of patients who underwent robotic, laparoscopic, or open pancreatic resection from January 1, 2014, to September 12, 2024, have been identified in the hospital system using surgical keywords. After filtering for diagnoses, 4,713 cases of pancreatic malignancy have been selected. Further selection will continue for patients diagnosed with malignancies in the ampullary region, specifically those confirmed as pancreatic malignancies. Currently, information has been recorded for 600 pancreatic malignancy patients.

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Assessing equity in the distribution of high-technology medical equipment in China: evidence of surgical robot

By Ting Chen, Lu Ao AND Yuhang Pan . Jay Pan*

Against the backdrop of rapid economic development, people's demand for health services is growing, presenting a high-level and diversified situation. The health equity faces severe challenges in China. This study provides an empirical basis for relevant regulatory policies in the literature by analyzing the inequity of the distribution of surgical robots, a high-tech medical device, in China. Gini coefficient (Lorenz curve), Theil index, and spatial autocorrelation were used to demonstrate the equity and aggregation of surgical robot distribution among provinces and the eastern, central, and western regions. The results showed that the equity of surgical robot configuration in China is increasing, and the equity by population distribution was better than which by geographical area configuration; the east, central, and western regions showed differentiated distribution, and the central region is the best equity. Although the resource allocation in the eastern region was relatively high, the equity within the region needs to be strengthened, and the proportion of differences within the region is increasing through years; the distribution of technology had spatial aggregation, and there were also clustered abnormal points, suggesting anchor points for the optimization of technical resources.

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I. Background

From the 1978 Alma-Ata Declaration proposing “primary health care for all by 2000” to the 2015 UN Special Summit proposing “achieving sustainable development goals by 2030” (including guaranteeing “health for all throughout the life span”), the international community has always advocated a core concept that everyone should have equal access to health(United Nations 2015). Since 1978, when China began its market-oriented economic reforms, the country has made many substantive efforts to achieve universal health coverage, especially universal coverage of basic medical insurance and basic public health services(Tang et al. 2008). Health equity has been mentioned many times by the government, pointing out that the broad masses of people should enjoy equitable, accessible, systematic and continuous health services such as prevention, treatment, rehabilitation and health promotion(the Xinhua News Agency 2024).

Therefore, the concept of “health equity” has received more and more attention. Although published studies have reported inequalities in health status(Zhang and Kanbur 2005; Tang et al. 2008), health care services (National Health Commission 2021; Tang et al. 2008), health insurance (Yang et al. 2021), and health resources (including professional health personnel) (Liu et al. 2016) at the national level in China, only a few studies have focused on the equity of the distribution of high-tech medical equipment. In particular, a study of two common high-tech medical equipment in China (computed tomography (CT) and magnetic resonance imaging (MRI)) found that before 2004, the distribution of these two technologies in China was relatively equitable across the country, while the results after 2006 showed that the equity of high-tech equipment was low and its distribution was significantly correlated with regional socioeconomic level (He, Yu, and Chen 2013). Although China has made great breakthroughs in universal coverage of basic health services, the concentration of high-quality resources is still inevitable. In 2024, the CPC Central Committee issued the Decision on Further Deepening Reform and Promoting Chinese Modernization, emphasizing that deepening the reform of the medical and health system should "promote the expansion and sinking of high-quality medical resources and regional balanced layout" (the Central Committee of the Communist Party of China 2024). As one of the representatives of the current high-tech and cutting-edge medical and health technologies, surgical robots have been vigorously spread in China since the first Da Vinci surgical robot was introduced to China in 2006. Based on the advantages of technical effects and social benefits, however, China is still in the early stages of the spread of surgical robot technology. Studies have shown that since the advent of surgical robots in 2000, more than 50% of hospitals in the United States have been equipped with surgical robots and performed operations by 2015. However, since the first use of surgical robots in China, as of 2021, it has also been 15 years, and only 224 medical institutions are equipped with surgical robots, accounting for 0.61% of the number of hospitals in the country. It can be foreseen that there is still a large market space for technology. At present, developed countries such as the United States (Mohanty et al. 2022), Switzerland (Stalder et al. 2024), Australia and New Zealand (Royal Australasian College of Surgeons 2021) have explored the inequity of the distribution of surgical robots, and found that there were differences in regional factors such as the professional level of institutions, the economic level and rural or urban. There is still a lack of relevant empirical research in China. Therefore, this study explored the equity of the distribution of surgical robots, a high-tech medical device, in China, and aim to provide empirical evidence and basis for literature and related regulatory policies.

II. Methods

The data used comes from the operating data of robot service providers who currently have an absolute advantage in the market share of surgical robots (accounting for more than 90% of the business volume of some types of surgical robots in mainland China). The permanent population data comes from the "China Statistical Yearbook", and the geographical area of each province (autonomous region, municipality) comes from the statistical yearbook of each province. According to the regional grouping of the National Bureau of Statistics, the 31 provinces, autonomous regions, and municipalities in China, except for Taiwan Province, Hong Kong and Macao Special Administrative Region, are divided into three regions: the east (Beijing, Tianjin, Hebei, Shandong, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong and Hainan, a total of 11 provinces); the middle (Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan, a total of 8 provinces) and the west (Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang, a total of 12 provinces).

This study mainly used the Gini coefficient (Lorenz curve), the Theil index and spatial autocorrelation analysis to explore the equity of the adoption of surgical robot (the purchase and configuration of technology). The Gini coefficient is often used to measure the distribution gap of a certain social resource. Scholars often introduce it into the field of health and use it to evaluate the equity of health resource allocation(Berndt et al. 2003). The value range of the Gini coefficient is 0-1. According to international practice, 0.4 is used as the "warning line" of the distribution gap. <0.2 indicates absolute equity, 0.2-0.3 indicates relative equity, 0.3-0.4 indicates normal conditions, 0.4-0.6 indicates relative inequity, and >0.6 indicates high inequity (JIN et al. 2015). The Theil index ranges from 0 to 1. The smaller the value, the equitableer the resource allocation. At the same time, the Theil index can further calculate the differences within and between different regions and show the main sources of inequity (Theil 1967). Furthermore, the global Moran’s I index was used to analyze the spatial autocorrelation and its changing trend of surgical robots in China as a whole. The value of Moran’s I index is generally [-1,1], <0 indicates that the technical equipment resources between regions are spatially negatively correlated, equal to 0 indicates random distribution, and >0 indicates spatially positive correlation. Local Moran’s I is used to identify the spatial autocorrelation of specific locations and their neighborhoods, and can identify local patterns such as hot spots (high-value clustering areas), cold spots (low-value clustering areas) or outliers (high-low clustering or low-high clustering) (Mathur 2015). The standard addresses of medical institutions were collected from the official websites of each institution, and the longitude and latitude coordinates were converted using the AutoNavi Open Platform platform. The data analysis and drawing software for this study was R 4.2.3.

III. Results

Table S1 shows the demographic characteristics and surgical robot density of 31 provinces. By mid-2022, the four municipalities (Beijing, Shanghai, Tianjin and Chongqing) had a higher per capita number of surgical robots, with Beijing having the highest (1327.84/billion people). Although Guangdong Province had a large number of devices (21 units), the per capita number of robots was only in the middle, and Tibet had not yet implemented a robot-assisted surgery. Figure 1 shows the distribution and per capita distribution of surgical robots in 31 provinces in China. The red bar graph represented the absolute number of surgical robots, and the depth of the map represented the per capita number of surgical robots. It can be seen that although the high number index was mainly concentrated in the eastern coastal areas, the per capita technology volume had relatively high values in all the eastern, central and western regions, but overall, the technology volume in the western region is relatively small.

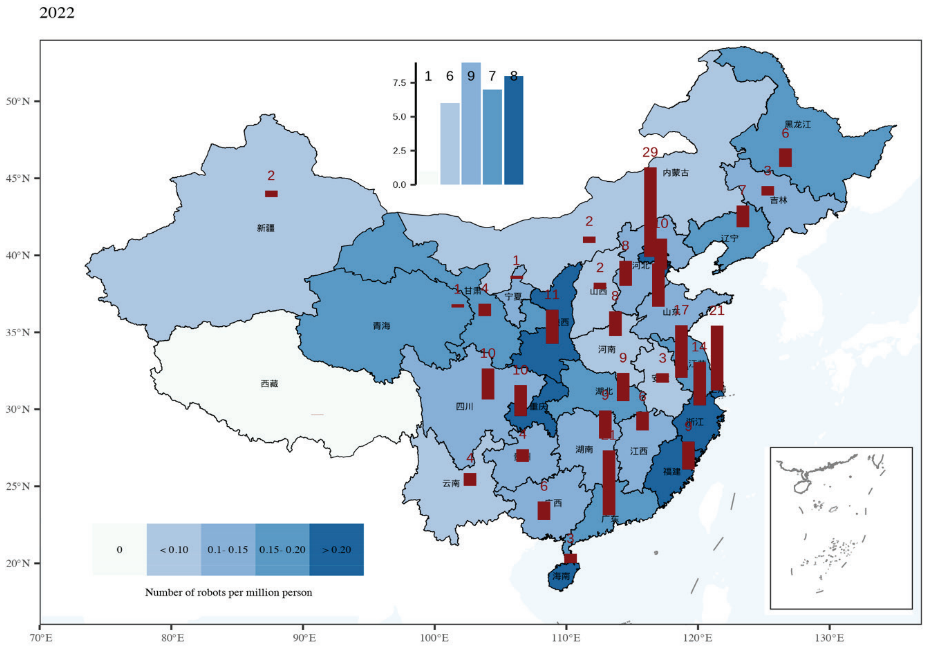

Figure 1. The Distribution of Surgical Robots In China

Notes: The red bar graph indicates the number of surgical robots, and the depth of color of the map indicates the number of surgical robots per capita.

The left plot of Figure 2 shows the Lorenz curve and the Gini coefficient from 2007 to 2022 according to population distribution. The darker the color of the Lorenz curve presented the newer the year. The allocation of technical resources among provinces had shown a trend of becoming more equitable. The Gini coefficient showed that the configuration of surgical robots in China was relatively inequity in the early stage, but the equity increased in the later stage, reaching a relatively equitable state in 2021 and 2022. The right plot shows the Lorenz curve and Gini coefficient calculated by cumulative geographical area. The overall trend was consistent with the results of population calculation, but the technical configuration based on area distribution was more inequity than which by the population configuration.

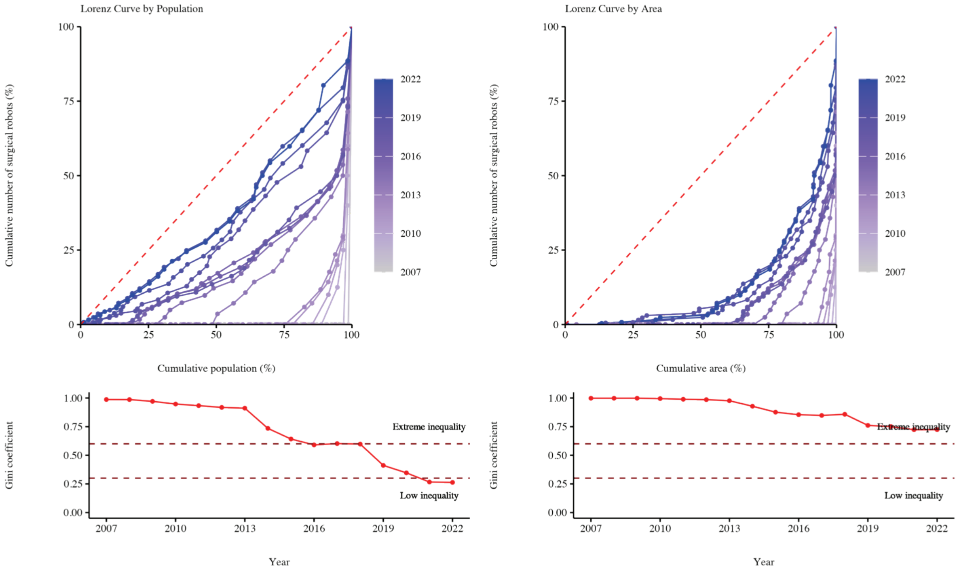

FIGURE 2. LORENZ CURVE AND TREND OF GINI COEFFICIENT OF SURGICAL ROBOTS IN CHINA

Figure 3 shows the equity of technology allocation in the eastern, central and western regions of China and the comparison with the national level. The left plot shows the Gini coefficient by population distribution. Overall, the equity of the central region was relatively higher. Although the eastern region generally had more technology allocation, the equity still needs to be improved. Over time, the allocation of technology resources among provinces had shown a trend of becoming more equitable through time, and by 2021 and 2022, it has basically reached a relatively equitable state. The right plot shows the cumulative calculation of the Gini coefficient by geographical area. The overall trend of change was consistent with the result of population calculation. The central region was still relatively more equitable, followed by the eastern region, the rate of reduction of inequity was faster, while the western region was still relatively consistent with the national level, and until 2022, it still showed a high degree of inequity. The western region of China is relatively sparsely populated, and more attention should be paid to the accessibility of geographical space when considering resource allocation.

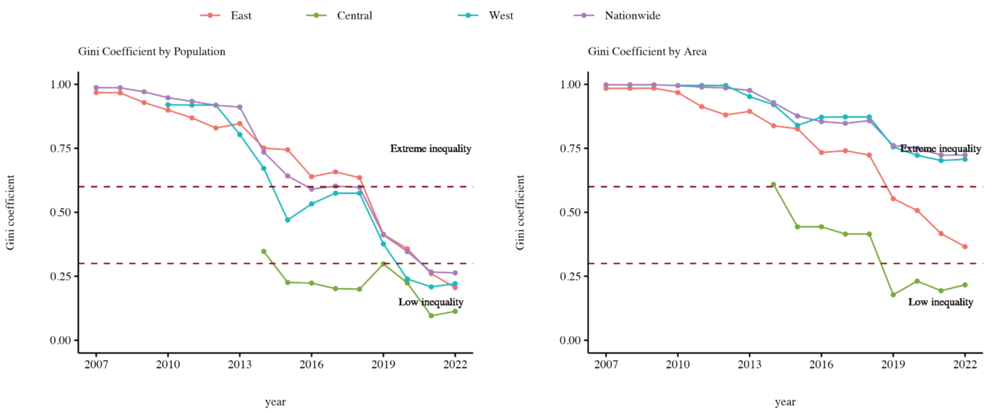

Figure 3. Trend of Gini coefficient of Surgical Robots In Different Area

Table 1 shows the Theil index of surgical robot configuration in China from 2014 to 2022, as well as the contribution rate of intra-regional and inter-regional differences in the eastern, central and western regions (calculated by intra-regional or inter-regional differences/total differences). It can be seen that as the years go by, the total Theil index decreased and equity increased. In the early years, regional differences dominated the total inequity differences, reaching a maximum of 87.9%. However, as the central and western regions gradually began to adopt surgical robots, the differences between regions gradually decreased, and the differences within the regions became dominant. By 2022, the differences within the regions exceeded half, accounting for 52.1%, indicating that in the process of technical equipment configuration, attention should also be paid to the relative "cold spots" of surgical robot equipment resources.

Table 1—Theil Indexs and Contribution Percent Between and Within the Area through years

Year	Theil Index	Contribution percent between the area (%)	Contribution percent within the area (%)
2014	0.90	16.65	83.35
2015	0.59	12.10	87.90
2016	0.48	16.50	83.50
2017	0.49	14.02	85.98
2018	0.50	19.62	80.38
2019	0.29	36.45	63.55
2020	0.23	45.65	54.35
2021	0.17	44.50	55.50
2022	0.18	47.91	52.09

Taking 2022 as an example, this study further conducted spatial autocorrelation analysis. The results showed that the global Moran’s I index of surgical robots in China was 0.11, $P < 0.05$, and there was a significant spatial positive correlation and a spatial aggregation distribution. Figure S1 shows the local autocorrelation results. It can be seen that Tianjin, Shanghai and Xinjiang showed significant spatial aggregation. Figure S2 is about the Local Indicators of Spatial Association (LISA), in which red represents a high-value area and is adjacent to a high-value area (H-H), for Tianjin and Sichuan Province; blue represents a low-value area and is adjacent to a low-value area (L-L), for Inner Mongolia, indicating that Inner Mongolia and its surrounding areas are areas lacking technical resources; and outliers, that is, high-value areas are surrounded by low-value areas (H-L), and Jiangsu and Zhejiang, indicating that adjacent provinces such as Anhui and Jiangxi might be relatively abnormally low values, requiring more attention to equity.

IV.Summary and Further Plan

In this essay, we briefly described the equity of surgical robots as a representative of high-tech medical technology, and the distribution among provinces and regions in China, and demonstrated the evolution and current situation of the adoption of high-tech medical technology among regions in China. At present, compared with developed countries such as Europe, the United States, and Australia, the technical quantity and relative quantity of surgical robots in China are still very insufficient, and the market requirement for surgical robots is relatively large. Before the large-scale popularization of technology, it is necessary to strengthen the planning and attention to the equity of technology distribution, especially the increasingly severe regional differences, as well as the abnormal points of clustered distribution indicate the objective technology gap. At the same time, the pioneers of technology can provide empirical experience of technology for the later adopters, and provide an evidence basis for the "appropriate" diffusion of technology.

At present, this study has conducted a preliminary analysis of the current status of the use of Da Vinci surgical robots in China and the macro and meso-level influencing factors (including equity analysis and institutional factors such as market competition and scale), and completed a systematic literature review, some expert consultation and micro interview analysis, and constructed a theoretical framework for the study of micro-level influencing factors. Next, this study will further dig the differences and equity of distribution, and explore its patterns and causes through further questionnaires and interviews, so as to provide an evidence basis for the formulation of relevant research policies on surgical robots in China.

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手术机器人对手术风险和不确定性的影响：一项全面的经济评估

陈尔默*

摘　要　临床实践中手术机器人的广泛采用与健康技术评估（HTA）研究结论的不一致形成了鲜明对比。这种差异可能源于基于均值的 HTA 工具无法捕捉手术机器人的风险缓解能力。尽管手术机器人可能不会从根本上改变某些手术的临床机制，但它们的标准化和稳定性缓解了人类操作固有的不确定性，这可能带来更具有一致性的手术结果。这种分布性地特征对 HTA 评估具有讨论价值。

本文评估了在医疗机构中引入手术机器人对服务结果风险和不确定性的影响。住院时间、临床结果、术后并发症、临床错误和干预成本的变化都被纳入评估范围。利用市场主导的手术机器人供应商的服务记录和覆盖中国四千多家医院的 IT 供应商的统计数据，本文分析了一个包含 4,231 家医院、30,936 个医院季度、涵盖15年（2007-2022年）和29个省份的样本集。

为了分析引入手术机器人对医院的整体影响，评估基于医院 × 季度的模型点进行，因为只有分组属性包含分布信息。本文引入了一种时变的双重差分方法来识别引入手术机器人的因果效应。采用混合因果推断检验以确保结论的稳健性。此外，我们还提出了一种新的专为方差分解设计的广义线性回归方法，用于对组内不确定性进行分析。

分析结果表明，引入手术机器人显著降低了手术死亡率，并大幅减少了与医疗错误和术后并发症相关的不确定性。这些好处是在具有一定水平但可接受的成本下实现的。这些发现强调了在手术机器人健康技术的经济评估中考虑其风险缓解方面的重要性，将其纳入考虑可能使 HTA 的结果更为可靠。

关键词　手术机器人；死亡率；手术风险。

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一、背景介绍

近年来,随着机器人手术的普及率显著增加,手术程序的格局出现了明显的改变。一项对 73 家医院 169,404 名患者数据进行分析的队列研究发现，机器人手术在普通手术中的使用率大幅上升，从 2012 年的 1.8% 增加到 2018 年的 15.1% (Mehta et al.， 2022)。这一趋势表明机器人手术得到了广泛且迅速的采用，通常以传统腹腔镜微创手术的使用减少为代价。

机器人手术的采用受到多种因素的推动，包括技术进步和手术过程中提高的精度和控制潜力。(George et al.， 2018) 强调了机器人手术从怀疑到成为标准护理的演变。手术中机器人的整合得益于诸如达芬奇手术系统等发展，该系统允许进行复杂的手术，并具有增强的灵巧性和三维视野。

尽管技术有所进步,但关于机器人手术成本效益的担忧依然存在。一些研究表明，机器人手术可能比传统腹腔镜手术更昂贵，且并不总是提供额外的临床益处。例如，美国食品药品监督管理局（FDA）因缺乏支持其有效性的证据，对某些癌症治疗中使用机器人手术发出警告 (Food and Administration, 2023)。

机器人手术的临床益处仍是一个争论的话题。尽管一些研究报告了特定手术（如机器人辅助肝切除术）的改善结果 (Lafaro et al.， 2020)，但其他研究在比较腹腔镜或开放手术时发现结果并无显著差异。一项比较机器人辅助肝切除术与腹腔镜肝切除术的荟萃分析发现，临床结果无显著差异 (Díaz et al.， 2015)。

机器人手术的快速增长也引发了关于外科医生有效利用这些先进技术所需的培训和专业知识的问题。与机器人手术相关的学习曲线是决定其有效性和安全性的关键因素。此外，采用机器人手术的经济影响，包括对医疗成本和资源分配的影响，是医院和医疗系统的重要考虑因素。

总之，尽管机器人手术在某些情况下显示出提高手术精度和患者结果的潜力，但其日益普及引发了对成本、功效以及在各种手术程序中持续评估其作用的重要问题。外科界和监管机构必须继续监控机器人手术的采用，以确保其使用得到强有力的临床证据支持，并积极促进患者护理。

机器人手术对临床结果的影响一直是广泛争议的话题，研究结果既有正面也有负面。一些研究表明，机器人手术可以提高精度并减少术后并发症，而其他研究则认为它并不总是比传统手术方法提供显著优势，有时还会导致更高的成本和更长的手术时间。Kowalewski 等人进行的一项系统综述和荟萃分析 (Kowalewski et al.， 2021) 比较了腹腔镜和机器人辅助直肠切除术，发现大多数临床结果没有显著差异。

然而，他们指出机器人手术成本较高，这引发了对其成本效益的质疑。同样，Bongiolatti 等人（Bongiolatti et al.，2020）关于机器人辅助微创食管切除术的研究发现，机器人手术和开放手术在肿瘤学结果上没有显著差异，但强调需要进一步研究来验证机器人手术的益处。

从正面讲，Ramirez 等人（Ramirez et al.，2017）报告称，使用机器人辅助的微创根治性子宫切除术相比腹腔镜方法减少了转为开放手术的情况。此外，Vijayakumar 等人（Vijayakumar et al.，2020）在肿瘤学领域的系统综述表明，机器人手术可能提供更好的结果，但他们也指出需要更严格的研究来支持这些发现。

相反，Audenet 等人（Audenet et al.，2020）的研究发现，机器人辅助根治性膀胱切除术后出现了非典型复发，表明机器人手术存在潜在风险。O’Sullivan 等人（O’Sullivan et al.，2018）对肺叶切除术方法进行的荟萃分析发现，机器人手术、视频辅助胸腔镜手术和开放手术的结果没有显著差异，这表明机器人手术并不总是提供更优越的结果。

Muaddi 等人（Muaddi et al.，2021）进行的系统综述概述进一步突显了机器人手术对临床结果的不一致影响，发现机器人辅助根治性前列腺切除术提供了一些益处，如较少的生化复发和改善的恢复质量，但这些益处仅在术后六周内观察到。作者得出结论，需要更多研究来确定机器人手术的真实价值。

汇总来看，文献表明，尽管机器人手术有可能提供某些益处，如提高精度和减少转换率，但它并不普遍优于传统手术方法。采用机器人手术的决定应基于对其临床益处、成本效益以及支持其使用的强有力证据的仔细评估（Kowalewski et al.，2021；Bongiolatti et al.，2020；Ramirez et al.，2017；Vijayakumar et al.，2020；Audenetet al.，2020；O’Sullivan et al.，2018；Muaddi et al.，2021）。

总之，先前的研究并未显示出引入医疗机器人在手术中具有一致的显著益处(Borden et al.，2007)，而在现实中，它却变得越来越流行。需要挖掘更多的推动因素。队列研究中的样本量太少，无法得出可靠的超出预期的结果，如风险和不确定性。这促使我们采用更大的数据集进行回顾性分析。

我们研究了引入医疗机器人对死亡率变化的影响。结果表明，医疗机器人可以显著降低手术死亡率。这是医疗错误研究项目的一部分。

二、数据

2.1 数据源

本文的研究基于一家在市场上占据主导地位的医疗机器人供应商在中国大陆的服务记录，记录了每个病例的医院名称、手术日期和手术类别。同时，我们也使用一家信息技术提供商的统计报告。该报告是一份基于内部数据的统计报告，样本涵盖 2007-2022 日历年的中国大陆 6252 家医院。每个医院每个月的样本数、死亡率、平均费用、费用差异和住院天数，以及每个手术或科室的类别都有报告。此外，报告还提供了医院的地点、级别和等级。

两个数据源可以通过医院和日期进行匹配。分析覆盖 6252 家医院，其中 97 家有医学机器人的手术记录，覆盖了手术记录的 28328/314152 = 9%。经过数据清洗，4231 家医院，30936 个医院 × 季度进入统计分析。

2.2 数据清洗与筛选

除非使用样本量大于某个门槛水平的模型点统计数据，否则回归不会得到稳定的结果。

我们使用一个基于常识的回归模型来判断这个合理的门槛水平。

$$\mathrm{ExpecedCost}_{i,t} \sim \mathrm{X}_i + \mathrm{I}_t + \mathrm{SampleSize}_{i,t}, \tag{1}$$

该模型模拟了不同地区和时期的成本效应。合理的结果应显示成本随时间增加，并且从大城市到低收入地区的差异为正。下图显示了使用不同样本量门槛水平对系数进行的估计。

对于样本量大于 30 个模型点的估计，可以生成稳定且合理的结果。在我们的论文中，我们使用样本量大于 50 个模型点以获得可靠的结果。

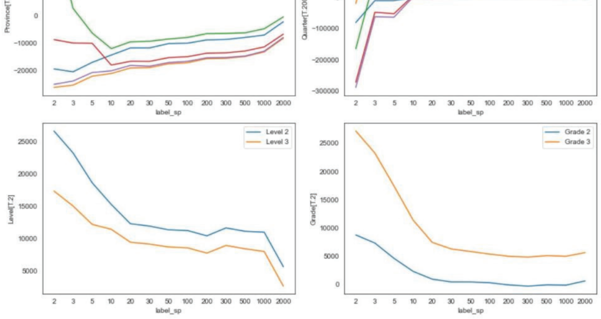

图1. 阈值测试曲线图

三、面板模型

3.1 面板分析模型

对于死亡率的分析， 本文的回归模型使用

$$\mathrm{DeathRate}_{i,t} \sim \mathrm{Robot}_{i,t} + \mathrm{X}_i + \mathrm{I}_t, \quad \omega = \mathrm{SampleSize}_{i,t}, \tag{2}$$

其中 $\mathrm{Robot}_{i,t}$ 是机器人使用的程度， 采用例数 （Num__of_Robot） 和例数占比 （Robot__Rate） 两种口径。这是因为统计记录数据是根据样本得出的，而不是完整的记录，因此例数占比的评估不够准确。但例数占比是对效果进行显著性检验所必需的。因此，在分析过程中要同时考虑这两个因素。

考虑两种固定效应。一种是直接使用医院的唯一 ID，这种方法比较简单，但受限于统计结果数据中的一些缺失结果。另一种是使用医院所在的省、医院等级和医院级别来代替，这可能会丢失一些信息，但结果会更加稳健。我们对两种方法均加以使用。

对于住院时长的建模， 本文的回归模型使用

$$\mathrm{InHospitalDays}_{i,t} \sim \mathrm{Robot}_{i,t} + \mathrm{X}_i + \mathrm{I}_t, \quad \omega = \mathrm{SampleSize}_{i,t}, \tag{3}$$

其中 $\mathrm{InHospitalDays}_{i,t}$,t 代表第 t 年第 i 个医院的住院病历的平均入院时长。其余的是定与死亡率分析部分相同。

对于费用方面，关于平均费用的建模使用

$$\mathrm{ExpectedCost}_{i,t} \sim \mathrm{Robot}_{i,t} + \mathrm{X}_i + \mathrm{I}_t, \quad \omega = \mathrm{SampleSize}_{i,t}, \tag{4}$$

其中 $\mathrm{ExpectedCost}_{\mathrm{i,t}}$ 代表第 t 年第 i 个医院的住院病历的例均费用。而对于费用的波动性方面，回归模型使用

$$\mathrm{VarianceCost}_{i,t} \sim \mathrm{Robot}_{i,t} + \mathrm{Robot}_{i,t}(1-\mathrm{Robot}_{i,t}) + \mathrm{X}_i + \mathrm{I}_t, \quad \omega = \mathrm{SampleSize}_{i,t}, \tag{5}$$

其中 $\mathrm{VarianceCost}_{\mathrm{i,t}}$ 代表第 t 年第 i 个医院的住院病历的例均费用的方差。值得注意的是，此处引入了交乘项 $\mathrm{Robot}_{i,t}(1-\mathrm{Robot}_{i,t})$ 来对组内方差和总方差进行分离，分离的具体原理见附录。

3.2 面板分析模型结果

3.2.1 死亡率的分析结果 以机器人手术例数的为自变量，对医院死亡率建模的模型结果如下表所示。

	死亡率的分析结果			
机器人手术例数	1.65E-06	1.12E-06	-6.19E-06	-2.12E-06
机器人手术例数的p-value	0.0838	0.2436	0.0000	0.0094
固定效应：时间		Yes	Yes	Yes
固定效应：医院				Yes
固定效应：科室				
固定效应：省份			Yes	
固定效应：医院等级			Yes	
固定效应：医院级别			Yes	
样本点数	30,936	30,936	30,936	30,936
F统计量	2.9890	5.1351	100.2786	17.8164
拟合优度	0.0001	0.0104	0.2454	0.7417

结果表明，在控制时间和医院的固定效应（直接和间接）的情况下，机器人手术次数与死亡率之间存在明显的负相关关系。如果不控制固定效应，尤其是医院效应，结果就会变得复杂。这是由于医院在引进机器人时存在选择偏差造成的，这种偏差很常见，因为机器人的手术是非常昂贵的。

3.2.2 平均住院时长的分析结果以机器人手术例数的为自变量，对医院死亡率建模的模型结果如下表所示。

结果表明，引入机器人手术对平均住院时长的影响没有显著的效果，这与其他研究得到的结论形成了相互印证。

	平均住院时长的分析结果			
机器人手术例数	-1.33E-01	-9.52E-02	-2.99E-02	7.37E-01
机器人手术例数的p-value	0.8756	0.9121	0.9729	0.5969
固定效应：时间		Yes	Yes	Yes
固定效应：医院				Yes
固定效应：科室				
固定效应：省份			Yes	

固定效应：医院等级			Yes	
固定效应：医院级别			Yes	
样本点数	30,904	30,904	30,904	30,904
F统计量	0.0245	0.2178	0.9134	0.3736
拟合优度	0.0000	0.0004	0.0030	0.0568

3.2.3 平均成本的分析结果 以机器人手术例数的为自变量，对住院病历例均成本的模型结果如下表所示。

	例均成本的分析结果			
机器人手术例数	2.72E+01	2.63E+01	1.93E+01	3.34E+00
机器人手术例数的p-value	0.0000	0.0000	0.0000	0.0017
固定效应：时间		Yes	Yes	Yes
固定效应：医院				Yes
固定效应：科室				
固定效应：省份			Yes	
固定效应：医院等级			Yes	
固定效应：医院级别			Yes	
样本点数	30,936	30,936	30,936	30,936
F统计量	744.2504	17.9099	113.2246	9.5432
拟合优度	0.0235	0.0353	0.2686	0.6060

从结果可以看出引入手术机器人对例均成本带来显著的大幅提升，这与常识和预期完美吻合。该部分的结果也印证了本文数据和方法的有效性。

3.2.4 成本方差的分析结果 以机器人手术占比的为自变量，对住院病历成本方差的模型结果如下表所示。值得注意的是，附录展示的方差分离定理要求该回归使用机器人手术占比而不是例数进行回归。

分析结果显示，机器人手术费用的组内方差并未显示出比传统手术更大的不确定性，没有证据表明机器人手术的引入显著引入了新的风险因素。

	成本方差的分析结果			
机器人手术例数	3.71E+12	1.85E+12	-1.34E+12	-6.30E+12
机器人手术例数的p-value	0.9400	0.9702	0.9784	0.9318

固定效应：时间		Yes	Yes	Yes
固定效应：医院				Yes
固定效应：科室				
固定效应：省份			Yes	
固定效应：医院等级			Yes	
固定效应：医院级别			Yes	
样本点数	30,936	30,936	30,936	30,936
F统计量	0.0185	0.4753	0.6423	0.7605
拟合优度	0.0000	0.0010	0.0021	0.1092

四、时变双重差分分析

4.1 时变双重差分分析建模

在本节中，我们构建了一个时变双重差分模型，以判断上述观察到的属性是否实际上是由引入手术机器同样，我们使用模型点作为医院 × 季度，并用是否已经为某些手术引入了手术机器人作为处理触发器进行标记。

对于方差模型以外的模型，回归方程设计如下

$$\mathrm{Measure}_{i,t} = \alpha + \mu_i + \lambda_t + \theta \mathrm{Robot\_Rate}_{i,t} \times \mathrm{Post}_{i,t} + \mathrm{X}_i, \tag{6}$$

其中 $\mathrm{Measure}_{i,t}$ 是目标测量值，可以表示为“死亡率”、“平均住院天数”和“预期成本”。此外，Post_t 表示模型点是否已经处于处理状态，这意味着

$$\mathrm{Post}_{i,t} = \mathrm{I}(\mathrm{Robot\_Rate}_{i,t} > 0).$$

对于针对方差的模型，回归方程设计如下

$$\begin{aligned} \mathrm{Variance}_{i,t} = \alpha + \mu_i + \lambda_t + \theta_1 \mathrm{Robot\_Rate}_{i,t} \times \mathrm{Post}_{i,t} \\ + \theta_2 \mathrm{Robot\_Rate}_{i,t}(1 - \mathrm{Robot\_Rate}_{i,t}) \times \mathrm{Post}_{i,t} + \mathrm{X}_i, \end{aligned} \tag{7}$$

其中的符号系统与上式相同。

表 1 期望成本的分析结果

	(1)	(2)	(3)	(4)
	cost_exp	cost_exp	cost_exp	cost_exp
robot_rate	90858.039***	67088.417*	64013.461*	63159.306*
	(27176.581)	(37267.088)	(34551.897)	(35230.905)
hospital	Controlled			
level		-571.574***		-477.949***
		(59.393)		(60.474)
grade		1597.509***		1539.725***
		(164.393)		(148.454)
Province				Controlled
_cons	7959.176***	5215.464***	23148.462***	19944.458***
	(1884.634)	(1847.924)	(3502.365)	(3627.37)
Observations	30936	30936	30936	30936

表 2 平均住院天数的分析结果

	(1)	(2)	(3)	(4)
	inhos_exp	inhos_exp	inhos_exp	inhos_exp
robot_rate	670.501	-475.142	88.884	32.562
	(873.401)	(467.394)	(182.644)	(214.883)
hospital	Controlled			
level		-44.583		-21.735
		(44.362)		(21.192)
grade		122.105		128.314
		(113.373)		(118.296)
Province				Controlled
_cons	2171.183	-203.805	127.005*	-188.545
	(1671.862)	(199.519)	(71.862)	(247.309)
Observations	30904	30904	30904	30904

表 3 死亡率的分析结果

	(1)	(2)	(3)	(4)
	death_rate	death_rate	death_rate	death_rate
robot_rate	-.05***	.031	.026	.026
	(.014)	(.021)	(.024)	(.024)
hospital	Controlled			
level		0		0
		(0)		(0)
grade		0		0
		(0)		(0)
Province				Controlled
_cons	.005	.005	.012**	.011**
	(.005)	(.005)	(.005)	(.005)
Observations	30936	30936	30936	30936

4.2 时变双重差分分析结果

5 结论

从上述计量结果中可以看出，无论是横截面分析还是双重差分的分析结果，引入手术机器人对医院结果的影响都是相似的。主要发现如下：

- 手术机器人将显著帮助降低医院内的死亡率。
- 尽管平均成本显著增加，但方差在一定程度上得到了控制。
- 住院时间没有显著影响。

总之，本文表明引入手术机器人显著降低了手术死亡率，并大幅减少了与医疗错误和术后并发症相关的不确定性。这些好处具有一定的成本，但是在可接受的成本下实现的。这些发现强调了在手术机器人健康技术的经济评估中考虑其风险缓解方面的重要性。

6 声明

该版本为过程稿，最终结果可能会有所不同。

表 4 成本不确定性的分析结果

	(1)	(2)	(3)	(4)	(5)
	cost_var	cost_var	cost_var	cost_var	cost_var
robot_rate	1.846e+11	-3.172e+11	1.027e+11	7.298e+10	-6.194e+13
	(3.761e+11)	(3.121e+11)	(1.135e+11)	(9.318e+10)	(6.001e+13)
hospital	Controlled				
level		-1.560e+10		-1.388e+10	1.925e+11
		(1.278e+10)		(1.009e+10)	(1.406e+11)
grade		5.527e+10		5.204e+10	-9.663e+11
		(5.575e+10)		(5.632e+10)	(6.829e+11)
Province				Controlled	Controlled
cost_exp					4.601e+08
					(3.234e+08)
_cons	9.831e+10***	-1.070e+11	1.234e+10	-1.081e+11	-8.482e+12
	(3.096e+10)	(1.163e+11)	(1.822e+10)	(1.248e+11)	(6.204e+12)
Observations	30936	30936	30936	30936	30936

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机器人在中国医院的采用：分析计划

梁钧霆　潘聿航*

摘　要　我们实证研究了医疗机器人首次使用对中国医院科室绩效的影响。采用结合了双向固定效应（TWFE）和事件研究（Event-Study）方法的稳健分析框架，分析了从2013年1月到2022年12月的每日科室数据。我们的重点是量化首次使用这种先进的手术技术后，对科室总收入的影响。

由于中国前所未有的经济发展和日益增长的需求，中国已成为手术机器人增长最快的国家之一。这篇文章将研究中国医院，特别是科室里达芬奇手术系统（达芬奇外科手术系统）的技术采用情况。截至2022年，达芬奇手术机器人的母公司--直观复星Intuitive Fosun--被认为是最大的机器人辅助手术（Robotic Assisted Surgery）技术培训供应商，并获得FDA等认证。全球有超过70个国家近7000台达芬奇系统执行了超过1000万次微创机器人手术程序（薛瑞华、刘荣，2021）

达芬奇外科系统于2006年首次在中国引入，当时中国人民解放军总医院采用了该系统。从2006年至2023年，共有284家中国医院实施了达芬奇RAS系统。这一技术随后被2000多名外科医生用于多种手术，这些外科医生共进行了180多种手术，其中泌尿科的手术量最高，约为15万次。

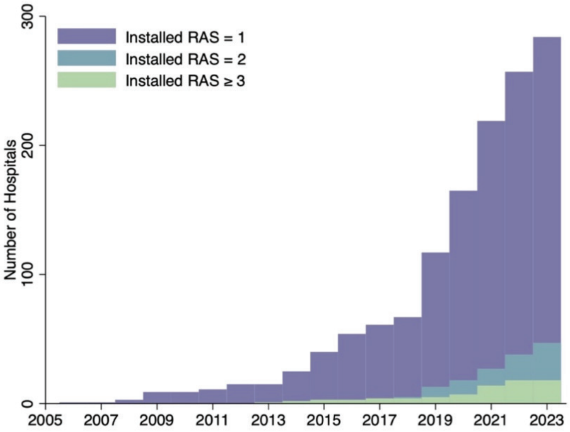

图 1. 中国拥有达芬奇手术系统的医院数量

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中国医院现有的达芬奇手术系统包括：DaVinci SP、DaVinci S、DaVinci Si和DaVinci Xi。我们主要关注达芬奇手术系统在不同类别和不同科室中进行的第一台手术。图1展示了达芬奇手术系统在中国医院的普及情况。可以观察到两个显著的增长期。第一个发生在2014年，当时配备达芬奇系统的医院数量几乎翻倍。第二次增长发生在2019年，配备达芬奇手术系统的医院数量从69家增加到119家。

图2描绘了安装达芬奇手术系统和其在各个外科部门首次使用之间的时间间隔。数据表明，普通外科和泌尿外科部门从系统安装到运行的时间间隔较短，可能是由于这些领域手术对达芬奇手术系统高需求和直接适用性。达芬奇手术系统可用于广泛的手续程序。在泌尿外科，它可以执行前列腺、肾脏和膀胱癌的微创手术。在普通外科领域，该系统可以在复杂的消化系统里进行胃癌和直肠癌的微创手术切除。胸外科则利用达芬奇的先进能力处理肺癌和食管癌等疾病。在妇科，达芬奇系统可以用于子宫切除，宫颈癌，卵巢癌等妇科癌症。在图2的分类基础上，我们的分析扩展到医院部门级别，包括小儿外科、胃结直肠外科、肝胆胰外科和甲状腺外科。如图3所示，只有甲状腺外科在达芬奇系统安装与其首次操作之间有显著间隔，这表明某些专业对达芬奇辅助手术机器人的应用仍处于开发阶段。

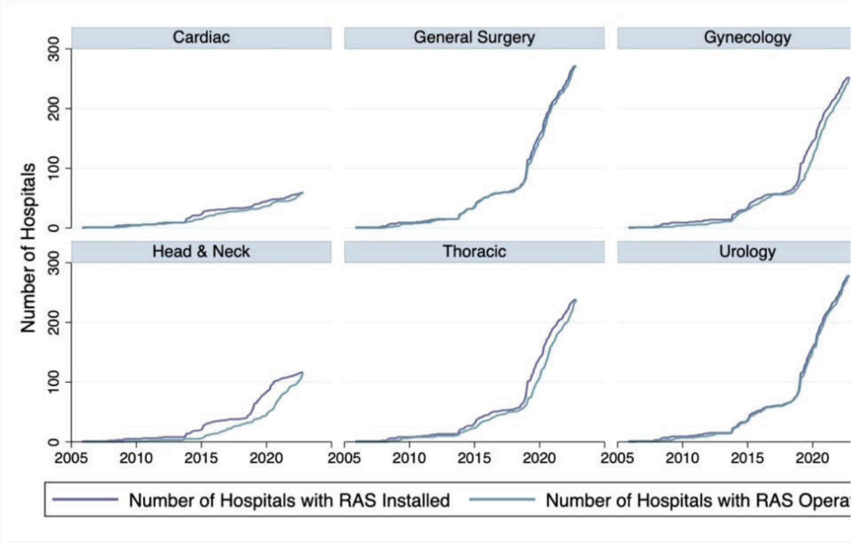

图 2. 医院各类别安装与首次使用时间间隔

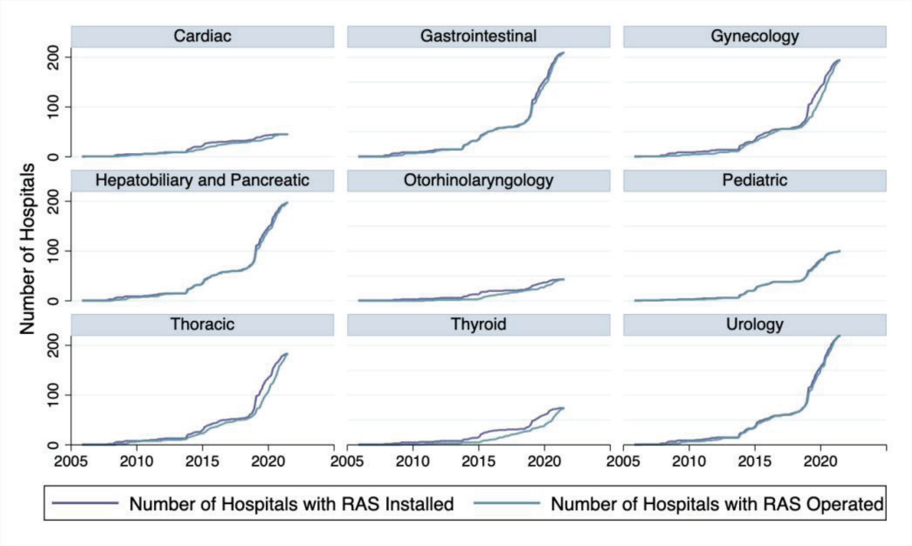

图 3. 医院各科室安装与首次使用时间间隔

数据

每个观测值代表单个病人整个住院期间的信息，病人级别的数据按科室级别每日汇总。数据包括病人特征、消费、住院时间和入院及出院日期。我们假设病人在住院期间每天花费相同，根据他们的总消费除以住院时间计算每日收入。

病人特征信息包含性别和年龄段。性别包括 1 代表男性，2 代表女性，3 代表未知。分配了六个年龄组：0-15 岁，16-30 岁，31-45 岁，46-60 岁，61-75 岁，以及 76 岁以上。计算了三种类型的病人特征：第一，为目前在医院的所有病人累计；第二，为刚入院的病人；第三，为刚出院的病人。

描述统计

表 1 中的摘要统计展示了控制组和处理组的医院层级指标概览，以月和周为单位进行分段统计。关键指标包括平均住院时间、患者数量、科室死亡率、总收入、自费收入和护理收入，覆盖了从 2013 年 1 月到 2022 年 12 月的时间段。

处理组的平均入院患者数量显著高于控制组，这表明配备达芬奇系统的医院可能处理更复杂或高级的病例。通常配备达芬奇系统的医院是具备更大接待能力的三甲医院。处理组的平均患者数量是控制组的 2.5 倍左右，其科室层级的总收入、自费收入和护理收入几乎是控制组的 4.7 倍。

Table 1:

Summary Statistics for Hospitals in Sample (in Thousands)

	(1) Month Control	(2) Month Treat	(3) Week Control	(4) Week Treat
Average Length of Stay	12.74	13.86	12.74	13.84
	(7.70)	(8.54)	(7.99)	(8.78)
Number of Patients	771.87	1898.07	186.13	457.23
	(1533.33)	(4941.31)	(365.08)	(1181.38)
Deathrate	0.0053	0.0068	0.0053	0.0068
	(0.0146)	(0.0187)	(0.0195)	(0.0243)
Total Revenue (1,000 Yuan)	10,200	47,900	2,465	11,600
	(25,600)	(117,000)	(6,220)	(27,900)
Self-pay (1,000 Yuan)	3,430	14,800	828	3,581
	(11,500)	(63,800)	(2,723)	(15,200)
Nursing (1,000 Yuan)	275	910	66	220
	(699)	(2,228)	(166)	(528)
Hospitals	2,854	66	2,859	66
Observations	123,449	4,662	512,059	19,303

Note: This table shows summary statistics for the sample of hospitals included in the main hospital-level analyses. All characteristics are at the hospital-month and hospital-week level spanning Jan 2013 to Dec 2022. Average length of stay is calculated by summing all patients length of stay then divided by total number of patients. Death-rate defined as how many death divided by total number of patients. Revenues is calculating at hospital department level in thousand of Yuan. Standard deviations presented in parentheses.

实证模型

本节介绍了用于评估达芬奇手术系统首次使用对各科室结果影响的实证分析。我们采用双重差分（DID）方法，利用包含医院和科室的面板数据来估计这一先进手术技术的因果效应。以下总结了实证模型、识别策略和主要发现。DID 识别策略利用了达芬奇系统在医院和科室首次使用时间上的差异。通过比较安装或首次使用前后的科室结果，并与尚未采用该系统的科室进行对比，DID 方法旨在将达芬奇系统的因果效应与其他混杂因素区分开来。

我们使用广义双重差分（TWFE）方法来估计达芬奇手术系统的影响，其中结果变量通过一组表示安装前后时间的事件时间虚拟变量回归。模型定义如下（He 和 Wang，2017）：

$$Y_{i,j,t} = \alpha + FirstProc_{i,j,t} + \rho_{i,j} + \vartheta_t + \epsilon_{i,j,t}$$

其中，$Y_{i,j,t}$ 表示医院 i、科室 j 在年份 t 的结果变量，$\mathrm{FirstProc}_{i,j,t}$ 是一个虚拟变量,如果医院 i、科室 j 在年份 t 已开始使用达芬奇机器人系统,则取值为 1,否则为 0。ϑ_t *and* $\rho_{i,j}$ 分别表示时间和医院科室的固定效应。标准误差在医院和科室层级进行聚类。

平行趋势检验与事件研究

在我们的实证策略中，回归模型中包括了医院科室和时间的固定效应，实质上采用了广义的双重差分模型。为了确保在达芬奇手术系统使用之前，处理组和对照组的结果趋势是平行的，我们实施了事件研究方法。参照 Jacobson 等人 (1993) 和 He 和 Wang (2017) 的方法，我们估计了以下方程：

$$Y_{ijt} = \alpha_{ij} + \delta_t + \beta_k \times \sum_{k=24}^{k\leq -12,\, k\neq 1} D_{ijt}^{k} + \epsilon_{ijt}$$

我们的结果变量 Y_{ijt} 是医院 i 科室 j 在时间 t 的不同收入的组合。Y_{ijt} 包括每日收入、入院总收入、出院总收入、自费服务收入、手术护理其他病理诊断、实验室诊断、影像学诊断、临床诊断、非手术治疗、手术治疗、康复收入。

虚拟变量 D_{ijt} 共同代表达芬奇首次使用事件，将医院 i 科室 j 首次安装达芬奇机器人系统的年份定义为 s_i 。我们定义 $D_{ijt}^{-12} = 1 \text{ if } t - s_i \leq -12$ 否则为 0。在基准模型中，我们控制了是医院 i 科室 j α_{ij} 和时间 δ_t.的固定效应。标准误差在医院层面上聚类；在未来的稳健性检查中，我们将在更小的类别层次上聚类。

基准结果

表2展示了每月的双重差分(DID)回归分析结果。这些结果表明，达芬奇系统的首次使用与平均住院时间的显著减少相关。首次使用程序的系数（标记为"first_proc"）为-1.181，在 5% 水平上显著。这表明在首次使用达芬奇系统后，患者的住院时间平均减少约一天，反映出机器人辅助手术程序的效率和效果提升。在平均住院时间的对数形式中，我们发现减少了-0.066%，在 5% 水平上显著。然而，死亡率的变化不具有统计上的显著性，系数接近零，这与外科医生的定性见解一致，即达芬奇系统在死亡率方面对患者风险无显著影响。

在科室收入方面，自费收入显著增加了 1.385，一个可能的解释是因为中国的保险政策不覆盖高端技术手术。除了达芬奇手术外，患者还可以选择由保险覆盖的

约 ¥5,000 的腹腔镜手术。然而，达芬奇手术的费用约为 ¥30,000，需患者自费支付。我们未观察到首次使用达芬奇系统对其他科室结果（例如总收入的系数为 0.099，护理收入的系数为 -0.196）有显著影响。不过，人均护理收入显著减少了 -0.1955（在 1% 水平上显著），这表明患者因住院时间缩短而产生的护理费用较低。

Table 2: Month DID Regression Results

VARIABLES	(1) avgstay	(2) deathrate	(3) patient	(4) lnavgstay	(5) lndeathrate	(6) lnpatient
First_proc	-1.182**	0.001	-74.987	-0.066**	0.001	0.113
	(0.502)	(0.000)	(55.465)	(0.030)	(0.000)	(0.125)
Obs.	126641	126641	126641	126641	126641	126641
Adjusted R-Square	0.524	0.367	0.736	0.587	0.380	0.839

VARIABLES	(7) lnzfy	(8) lnzfje	(9) lnhlf	(10) pplnzfy	(11) pplnzfje	(12) pplnhlf
First_proc	0.099	1.385*	-0.196	-0.016	0.958*	-0.217***
	(0.139)	(0.788)	(0.150)	(0.038)	(0.499)	[0.041)
Obs.	126641	126641	126641	126641	126641	126641
Adjusted R-Square	0.795	0.801	0.779	0.674	0.801	0.749

Note: All dependent variables are transformed using levels and natural logs where specified. Fixed effects at the hospital department and time level are included. Robust standard errors are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

事件研究结果

图 4 通过展示科室层面的自费收入点估计值及其 95% 置信区间来可视化动态效果。每个点表示事件前或事件后特定周或月的处理虚拟变量的估计系数。值得注意的是，自费收入在事件后第七个月开始表现出显著的增长趋势，显示出达芬奇系统对患者支出具有显著的积极影响。在第二张图中，护理收入在事件后第六个月开始呈现下降趋势，并在第十二个月及之后达到 5% 的显著性水平。

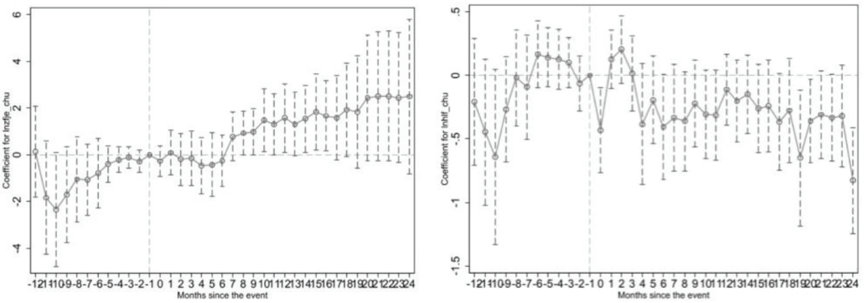

表 4. 自费收入以及护理收入的事件研究

稳健性检验

为了确保结果的稳健性，我们进行了额外的事件双重差分（Event DD）和分期双重差分（Stagger DID）分析，未发现相互冲突的系数。

异质性分析

我们进一步进行了针对特定科室的双重差分回归和事件研究分析，重点关注了心脏外科、普通外科、妇科、胸外科和泌尿外科等达芬奇系统使用频率较高的科室。此外，我们筛选了数据，集中于老年患者或极年幼患者较多的科室。最后，我们分别考察了达芬奇系统对男性和女性患者的影响。

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Health Economics Study of Robots and Laparoscopy for Hepatocellular Carcinoma Resection

By Xiao Liang, Haijing Guan, Junhao Zheng, AND Chenyue Yang

机器人与腹腔镜肝切除术治疗肝细胞癌的卫生经济学研究

梁霄 官海静 郑俊浩 杨辰越*

摘　要　背景：相比腹腔镜肝切除术，机器人肝切除术可以降低术后并发症发生率、住院时间，提升患者术后生命质量。然而，机器人肝切除术的费用较高，使用机器人肝切除术治疗肝细胞癌是否具有经济性，目前仍然缺乏中国证据。目的：探索机器人肝切除术相比腹腔镜肝切除术用于肝细胞癌切除术的临床价值与医疗费用。方法：我们回顾性收集了2016年1月至2023年7月浙江大学附属邵逸夫医院单一医疗团队内接受微创肝切除术的肝细胞癌患者的数据，将患者分为研究组即机器人肝切除组与对照组即腹腔镜肝切除组，进行倾向性评分匹配后，比较匹配前后的围术期指标和医疗费用，并以手术难度为协变量进行亚组分析，分析不同手术难度下两种术式围术期预后和医疗费用的差异。结果：共有277例患者被纳入本研究（腹腔镜肝切除组175例，机器人肝切除组102例）。在应用倾向性评分匹配控制混杂因素后，共162例患者（两组各81例）被纳入进一步分析。结果显示，机器人肝切除组相比腹腔镜肝切除组术中出血、术后并发症较少、中转开腹率较低，手术安全性更好。机器人肝切除组具有更高的医疗费用（82885.3元 vs. 58643.8元，$p<0.001$），然而，腹腔镜肝切除组除手术外的其他各项费用显著更高。亚组分析显示，在高难度肝切除术中，两种术式的费用没有显著差异。结论：对于肝细胞癌患者，机器人肝切除比腹腔镜肝切除具有更好的手术安全性和更高的医疗费用，同时，高手术难度患者采用机器人肝切除术更具有经济性。

一、引言

机器人肝切除术（robotic liver resection，RLR）作为一项新技术，相比腹腔镜肝切除术(laparoscopic liver resection，LLR)可能具有更佳的手术安全性，但其手术费用往往更高。因此，使用机器人切除术治疗肝细胞性肝癌(Hepatocellular

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carcinoma，HCC）是否具有经济学效应，目前仍然缺乏相关证据。

当今机器人肝切除相关的卫生经济学研究在国内外报道较少。2022 年 1 篇纳入了 4 篇相关文献的 meta 分析显示，RLR（20,205.92 美元）的成本远远高于 LLR（15,789.75 美元）。费用是制约 RLR 开展的重要因素（Ciria 等 2022）。然而，随着现代医学的发展，手术不仅是为了治愈，也是为了提高生活质量。2020 年 Mejia 等报道了 214 例肝切除患者，指出与 LLR 相比，RLR 尽管费用更高，但患者住院时间更短，对于小范围肝切除患者是更好的选择（Mejia 等 2020）。然而，2016 年我国学者根据机器人和腹腔镜肝左外叶切除手术的 39 例患者资料指出，对于肝左外叶切除，RLR 比 LLR 手术费用更昂贵，但在疗效和安全上差异无统计学意义（尹注增等 2016）。因此，RLR 是否能改善生活质量并具有成本效益仍然是一个争论。

2023 年的国际机器人肝切除专家指南指出，相较于 LLR，RLR 在肝脏相关疾病中具有独特的治疗价值，其成本效用值得未来继续研究（Liu 等 2023）。在泌尿外科、大肠外科等学科中，已有研究认为机器人手术具有成本效益，或者指出有利于提高机器人的应用率所需降低的费用（Simianu 等 2020；Song 等 2022）。

二、研究方法

开展真实世界研究，回顾性收集浙江大学附属邵逸夫医院 2016 年 1 月 -2023 年 7 月诊断为 HCC 的住院患者，根据患者的手术方式分为 RLR 组与 LLR 组，在描述性分析的基础上，通过倾向性评分匹配控制混杂因素，探索不同治疗方式对于治疗结局和医疗费用的净效益，并进行经济学评价。开展亚组分析，探索研究结果的稳健性。

正态分布的连续变量描述为平均值 ± 标准差，偏态分布的连续性变量描述为中位数（四分位距），分类变量描述为频率和百分比。将年龄、BMI、AFP、INR、ALB、AST、TBIL、Child 分级、血管浸润、手术难度、ASA 分级作为协变量纳入模型进行拟合，计算倾向性评分，进行最邻近法匹配。PSM 采用 SPSS 25.0 版本进行分析。将患者按照 IWATE 手术难度分级分为“低难度”“中等难度”“高难度”“专家难度”4 个亚组，进行亚组分析。

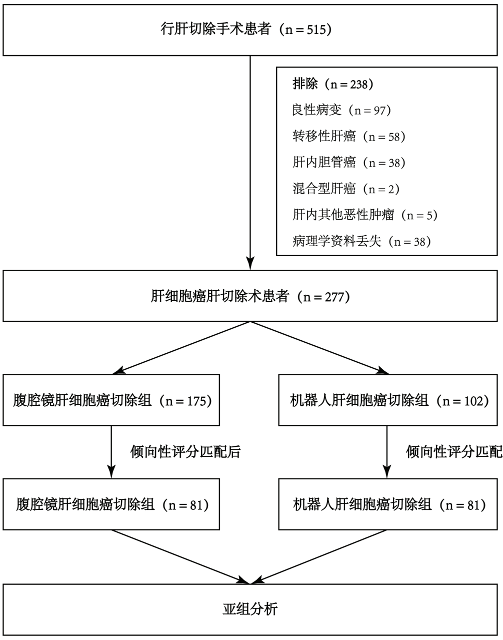

图1. 纳入、排除标准及流程图

三、结果

经纳入、排除标准筛选后，共有277例患者被纳入本研究，根据手术方式分为LLR组（175例）和RLR组（102例）。PSM后，两组各81例进一步进行比较分析。

3.1 患者基线指标

在倾向性评分之前，LLR组的BMI、AFP、PLT、INR、ALB、AST、肝硬化、Child-Pugh分级、门脉高压、IWATE手术难度分级与RLR组有显著性差异（均$p < 0.05$）。余指标均无显著性差异。经过倾向性评分匹配平衡基线指标后，162例患者（LLR组与RLR组各81例）纳入进一步分析，LLR组与RLR组的基线指标均无显著性差异。（附表1）

3.2 患者临床结局指标

在倾向性评分之前，LLR组的术中出血量（100.0 vs. 50.0 ml，$p < 0.001$）、

术中输血率（33［18.8%］vs. 10［9.8%］，p=0.045）、术后并发症发生率（35［20.0%］vs. 7［6.8%］，p=0.003）、术中转开放率（20［11.4%］vs. 0［0.0%］，p=0.001）、术后住院时间（6.0 vs. 5.0 day，p=0.001）、总住院时间（13.0 vs. 9.5 day，p=0.001）显著高于RLR组，其余指标均无显著性差异（均p≥0.05）。经过倾向性评分匹配平衡基线指标后，共162例患者（LLR组与RLR组各81例）被纳入研究，LLR组的术中出血量（100.0 vs. 50.0 ml，p=0.002）、术后并发症发生率（16［19.8%］vs. 7［8.6%］，p=0.043）、术后住院时间（6.0 vs. 5.0 day，p=0.005）、总住院时间（12.0 vs. 10.0 day，p＜0.001）显著高于RLR组，其余指标均无显著性差异（均p≥0.05）。（附表2）

3.3 患者费用结局指标

在倾向性评分之前,LLR组的住院总费用(57150.9 vs. 81432.5元,p＜0.001)、自付费用(16875.0 vs. 50333.4元,p＜0.001)、手术费用(6916.0 vs. 43424.9元,p＜0.001）显著低于RLR组，然而药物费用（15879.4 vs. 9955.6元，p＜0.001）、检查费用（1260.0 vs. 1160.0元，p=0.010）、护理费用（1164.0 vs. 989.6元，p=0.001）、耗材费用（21113.4 vs. 12094.4，p＜0.001）显著高于RLR组。经过倾向性评分匹配平衡基线指标后,共162例患者(LLR组与RLR组各81例)被纳入研究,LLR组的住院总费用（58643.8 vs. 82885.3元，p＜0.001）、自付费用（15972.7 vs. 50706.2元，p＜0.001）、手术费用（6616.0 vs. 43424.9元，p＜0.001）、其他费用（341.0 vs. 535.0元，p=0.004）显著低于RLR组，药物费用（16517.6 vs. 9975.0元，p＜0.001）、检查费用（1365.0 vs. 1115.0元，p=0.010）、护理费用（1174.0 vs. 988.6元，p=0.001）、耗材费用（21565.4 vs. 12069.4元，p＜0.001）显著高于RLR组。（附表2）

3.4 亚组分析结果

以IWATE手术难度分级为协变量进行亚组分析，结果显示，在“低难度”“中等难度”“高难度”3个亚组内，LLR组的住院总费用显著低于RLR组（低难度：46125.7 vs. 76647.9元，p＜0.001；中等难度：52692.8 vs. 76428.8元，p=0.003；高难度：67548.3 vs. 84725.0元，p=0.001），然而，在“专家难度”组内，LLR组与RLR组的住院总费用没有显著性差异（75709.0 vs. 88292.6元，p=0.325）。（图2）

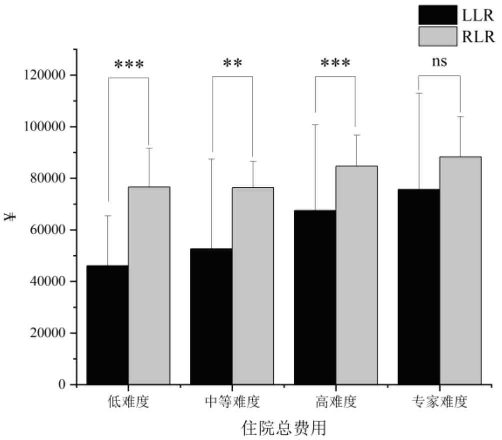

图 2. 住院总费用的手术难度亚组分析

注：

*** 代表 p ＜ 0.001

** 代表 p ＜ 0.005

ns 代表 p ＞ 0.05

将 IWATE 手术难度为“低难度”“中等难度”的患者合为低手术难度组，IWATE 手术难度为“高难度”“专家难度”的患者合为高手术难度组，进行亚组分析。结果显示，在两个手术难度亚组内，LLR 组的术中失血量（低手术难度：100.0(50.0-200.0) vs. 50.0(20.0-150.0)mL，p=0.013； 高手术难度：200.0(80.0-400.0) vs. 100.0(50.0-137.5)mL，p=0.024）、术后住院时间（低手术难度：5.0(4.0-7.0) vs. 4.0(3.0-5.5)days，p=0.010；高手术难度：6.5(5.0-9.0) vs. 5.0(4.0-7.0)days，p=0.046）、总住院时间（低手术难度：12.0(9.0-16.0) vs. 10.0(7.0-12.0)days，p=0.005； 高手术难度：13.5(10.0-16.0) vs. 9.5(8.0-12.0)days，p<0.001）均显著高于 RLR 组。在两个手术难度亚组内，LLR 组与 RLR 组的其余结局指标均无显著性差异。（附表 3）

四、小结

对于肝细胞癌患者，机器人肝切除比腹腔镜肝切除具有更好的手术安全性和更高的医疗费用，同时，高手术难度患者采用机器人肝切除术更具有经济性。

附表1. PSM前后LLR组与RLR组基线指标

基线指标						
	PSM前 (n=277)			PSM后 (n=162)		
	LLR (n = 175)	RLR (n = 102)	p值	LLR (n=81)	RLR (n=81)	p值
年龄 (SD), year	58.7±12.2	60.6±11.5	0.056	62.9±11.6	61.4±11.2	0.390
BMI (SD), kg/^{m}2	23.2±2.8	24.1±3.6	**0.021**	23.6±3.0	24.0±3.3	0.406
性别, n(%)			0.309			0.678
女	23(13.1)	18(17.6)		13(16.0)	15(18.5)	
男	152(86.9)	84(82.4)		68(84.0)	66(81.5)	
肿瘤最大径 (IQR), cm	2.6 (1.8-4.3)	3.0 (2.2-4.5)	0.163	2.5 (1.8-4.4)	3.2(2.2-4.7)	0.082
AFP (IQR), ng/mL	17.2 (3.4-277.5)	6.6 (2.5-110.2)	**0.048**	10.2 (3.2-139.8)	6.6 (2.6-110.2)	0.403
PLT (IQR), $\times 10^9$/L	126.0 (89.0-172.0)	143.5 (111.0-191.2)	**0.005**	124.0 (95.5-170.0)	138.0 (108.0-190.0)	0.050
PT (IQR), s	13.8 (13.1-14.6)	13.5 (13.0-14.2)	0.068	13.5 (12.9-14.1)	13.5 (13.1-14.2)	0.437
INR (IQR)	1.0 (1.0-1.2)	1.0(1.0-1.1)	**＜0.001**	1.0 (1.0-1.1)	1.0 (1.0-1.0)	0.307
TBIL(IQR), μmol/L	14.9 (11.1-21.1)	14.8 (11.2-19.1)	0.728	14.2 (9.6-21.3)	15.3 (11.4-18.8)	0.589
ALB (SD), g/L	39.4±4.8	40.9±4..5	**0.013**	40.2±4.4	40.0±3.6	0.794
AST (IQR), U/L	27.0 (18.0-40.0)	30.0 (23.8-38.0)	**0.026**	25.0 (17.0-41.0)	29.0 (23.5-38.0)	0.100
ALT (IQR), U/L	29.0 (22.0-39.0)	27.0 (19.0-42.3)	0.364	29.0 (21.5-39.0)	27.0 (19.0-41.5)	0.559
肿瘤数量, n(%)			0.819			0.658
单发	151(86.3)	87(85.3)		68(84.0)	70(86.4)	
多发	24(13.7)	15(14.7)		13(16.0)	11(13.6)	
肝硬化, n(%)	96(54.8)	41(40.2)	**0.016**	38(46.9)	32(39.5)	0.341
Child-Pugh分级, n(%)			**0.049**			1
A	159(90.9)	99(93.1)		78(96.3)	78(96.3)	
B or C	16(9.1)	3(2.9)		3(3.7)	3(3.7)	
门脉高压, n(%)	11(6.2)	0(0)	**0.028**	5(6.2)	0(0.0)	0.074
既往肝切除, n(%)	22(12.6)	14(13.7)	0.844	12(14.8)	12(14.8)	1
既往开腹手术, n(%)	56(32.0)	35(34.3)	0.693	27(33.3)	31(38.3)	0.512
既往新辅助治疗, n(%)	25(14.2)	10(9.8)	0.279	6(7.4)	9(11.1)	0.416
IWATE肿瘤位置 (IQR)	5.0(3.0-5.0)	5.0(3.0-5.0)	0.949	5.0(3.0-5.0)	5.0(3.0-5.0)	0.576
IWATE肿瘤大小 (IQR)	0.0(0.0-1.0)	1.0(0.0-1.0)	0.179	0.0(0.0-1.0)	1.0(0.0-1.0)	0.140
IWATE手术方式 (IQR)	0.0(0.0-4.0)	3.0(0.0-4.0)	0.195	0.0(0.0-4.0)	0.0(0.0-4.0)	0.946
IWATE靠近脉管 (IQR)	0.0(0.0-0.0)	0.0(0.0-0.0)	0.541	0.0(0.0-0.0)	0.0(0.0-0.0)	0.135
IWATE Child-Pugh (IQR)	0.0(0.0-0.0)	0.0(0.0-0.0)	**0.049**	0.0(0.0-0.0)	0.0(0.0-0.0)	0.988
IWATE手助腹腔镜 (IQR)	0.0(0.0-0.0)	0.0(0.0-0.0)	1	0.0(0.0-0.0)	0.0(0.0-0.0)	1

IWATE总分 (IQR)	6.0(5.0-9.0)	7.0(5.0-9.0)	0.176	6.0(4.0-9.0)	6.0(4.5-9.0)	0.57
IWATE难度分级, n(%)			**0.003**			0.916
低难度	27(15.4)	19(18.6)		16(19.8)	16(19.8）	
中等难度	82(46.9)	28(27.5)		29(35.8)	25(30.9)	
高难度	31(17.7)	35(34.3)		21(25.9)	23(28.4)	
专家难度	35(20.0)	20(19.6)		15(18.5)	17(21.0)	
ASA分级, n(%)			0.206			0.692
Ⅰ级	8(4.6)	1(1.0)		2(2.5)	1(1.2)	
Ⅱ级	155(88.6)	94(92.2)		72(88.9)	75(92.6)	
Ⅲ级	12(6.9)	7(6.9)		7(8.6)	5(6.2)	
Ⅳ~Ⅵ级	0(0.0)	0(0.0)		0(0.0)	0(0.0)	
医疗保险，n(%)			0.074			0.070
城镇职工基本医疗保险	164(93.7)	101(99.0)		74(91.4)	80(98.8)	
其他保险	11(6.3)	1(1.0)		7(8.6)	1(1.2)	
居住地，n(%)			0.803			0.727
本地	47(26.9)	26(25.5)		24(29.6)	22(27.2)	
外地	128(73.1)	76(74.5)		57(70.4)	59(72.8)	

附表2. PSM前后LLR组与RLR组结局指标

结局指标						
	PSM前 (n=277)			PSM后 (n=162)		
	LLR (n = 175)	RLR (n = 102)	p值	LLR (n=81)	RLR (n=81)	p值
手术时间 (IQR)，min	168.0 (125.0-240.0)	165.0(110.0-220.0)	0.263	180.0 (120.0-250.0)	160.0 (107.5-220.0)	0.134
切缘状态，n(%)			0.464			1
R0	172(98.3)	98(96.1)		80(98.8)	79(97.5)	
R1 or R2	3(1.7)	4(3.9)		1(1.2)	2(2.5)	
术中出血量 (IQR)，mL	100.0 (50.0-400.0)	50.0(50.0-112.5)	**<0.001**	100.0 (50.0-275.0)	50.0 (50.0-125.0)	**0.002**
术中输血情况，n(%)	33(18.8)	10(9.8)	**0.045**	12(14.8)	8(9.8)	0.339
术后并发症，n(%)	35(20.0)	7(6.8)	**0.003**	16(19.8)	7(8.6)	**0.043**
ClavienDindo分级, n(%)			**0.006**			0.062
No	140(80.0)	95(93.1)		65(80.2)	74(91.4)	
I or II	25(14.3)	6(5.9)		10(12.3)	6(7.4)	
III or IV or V	10(5.7)	1(1.0)		6(7.4)	1(1.2)	
术中转开腹情况，n(%)	20(11.4)	0(0.0)	**0.001**	5(6.2)	0(0.0)	0.069
住院期间再次手术，n(%)	0(0.0)	0(0.0)	/	0(0.0)	0(0.0)	/
围术期死亡情况，n(%)	0(0.0)	0(0.0)	/	0(0.0)	0(0.0)	/
术后住院时间 (IQR)，day	6.0(4.0-7.0)	5.0(3.8-6.2)	**0.001**	6.0(4.0-7.0)	5.0(3.5-6.0)	**0.005**
术后30天因并发症再入院，n(%)	3(1.7)	1(1.0)	1	2(2.5)	1(1.2)	1

总住院时间（IQR），day	13.0(10.0-16.0)	9.5(7.0-13.0)	**<0.001**	12.0(10.0-16.0)	10.0(8.0-12.0)	**<0.001**
住院总费用（IQR），元	57150.9 (44313.0-76302.3)	81432.5 (74644.9-90934.2)	**<0.001**	58643.8 (45171.2-75899.8)	82885.3 (75617.3-90501.2)	**<0.001**
自付费用（IQR），元	16875.0 (9911.2-23013.9)	50333.4 (46274.6-57632.8)	**<0.001**	15972.7 (8999.7-23056.8)	50706.2 (46796.8-57640.6)	**<0.001**
药物费用（IQR），元	15879.4 (11219.3-23459.2)	9955.6 (7687.4-14007.0)	**<0.001**	16517.6 (11994.0-24028.5)	9975.0 (7861.8-14117.4)	**<0.001**
手术费用（IQR），元	6916.0 (6302.0-7834.3)	43424.9 (42808.6-43897.9)	**<0.001**	6616.0 (6165.0-7481.4)	43424.9 (42754.1-43994.5)	**<0.001**
检查费用（IQR），元	1260.0 (930.0-2153.0)	1160.0 (673.0-1752.8)	**0.010**	1365.0 (1075.0-2340.0)	1115.0 (659.0-1602.0)	**0.001**
护理费用（IQR），元	1164.0 (879.0-1521.0)	989.6 (784.0-1291.3)	**0.004**	1174.0 (832.5-1555.0)	988.6 (779.9-1255.1)	**0.012**
耗材费用（IQR），元	21113.4 (15486.0-31411.4)	12094.4 (10839.8-18034.8)	**<0.001**	21565.4 (15899.2-32842.0)	12069.4 (10898.8-19094.2)	**<0.001**
其他费用（IQR），元	386.0 (182.0-722.0)	486.5 (246.5-851.8)	0.054	341.0(182.0-683.4)	535.0 (276.5-863.0)	**0.004**

附表3. IWATE手术难度亚组的结局指标分析

结局指标	低难度 + 中等难度（n = 86）			高难度 + 专家难度（n = 76）		
	腹腔镜（n = 45）	机器人（n = 41）	p值	腹腔镜（n=36）	机器人（n=40）	p值
手术时间（IQR），min	155.0 (100.0-223.8)	120.0 (85.0-180.0)	0.228	195.0(164.0-260.0)	187.5(150.0-240.0)	0.265
切缘状态，n(%)			/			1
R0	45 (100.0)	41 (100.0)		35 (97.2)	38 (95.0)	
R1_or_R2	0(0.0)	0(0.0)		1(2.8)	2(5.0)	
术中出血量（IQR），mL	100.0 (50.0-200.0)	50.0 (20.0-150.0)	**0.013**	200.0 (80.0-400.0)	100.0 (50.0-137.5)	**0.024**
术中输血情况，n(%)	7(15.6)	3(7.3)	0.393	5(13.8)	5(12.5)	1
术后并发症，n(%)	8(17.8)	3(7.3)	0.147	8(22.2)	4(10.0)	0.145
ClavienDindo分级, n(%)			0.063			0.341
No	37 (82.2)	38 (92.7)		28 (78.8)	36 (90.0)	
I_or_II	4(8.9)	3(7.3)		6(16.7)	3(7.5)	
III_or_IV_or_V	4(8.9)	0(0.0)		2(5.6)	1(2.5)	

术中转开腹情况，n(%)	3(6.7)	0(0.0)	0.274	2(5.6)	0(0.0)	0.428
住院期间再次手术，n(%)	0(0.0)	0(0.0)	/	0(0.0)	0(0.0)	/
围术期死亡情况，n(%)	0(0.0)	0(0.0)	/	0(0.0)	0(0.0)	/
术后住院时间（IQR)，day	5.0 (4.0-7.0)	4.0 (3.0-5.5)	**0.010**	6.5 (5.0-9.0)	5.0 (4.0-7.0)	**0.046**
术后30天因并发症再入院，n(%)	2(4.4)	1(2.4)	1	0(0.0)	0(0.0)	/
总住院时间（IQR)，day	12.0 (9.0-16.0)	10.0 (7.0-12.0)	**0.005**	13.5 (10.0-16.0)	9.5 (8.0-12.0)	**<0.001**

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基于真实世界数据的机器人辅助膝关节置换术临床效能和卫生经济学评价：进展报告

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摘　　要 我国膝关节疾病负担重，其中人工关节置换是治疗终末期膝关节炎最有效的方法。相比于传统的手术方式，机器人辅助膝关节置换具有定位精准度高、一致性强、术后疼痛减少以及功能恢复早等优点，有望改善患者预后。但机器人辅助膝关节医疗费用较传统手术高，是否具体经济性需要进行系统的卫生经济学评价。经过前期数据清理，本研究纳入281例机器人辅助全膝关节置换的患者，匹配年龄、性别、手术日期和术侧后，纳入281例接受非机器人辅助全膝关节置换的患者，初步完成针对43例机器人和43例非机器人辅助全膝关节置换患者的随访。初步随访发现，相比于非机器人辅助手术患者，机器人辅助手术患者手术时间较长（97.56分钟VS.79.05分钟，p<0.001），但术中引流量较少（1.42%　VS.9.25%术中引流量>0,p<0.001）；机器人组对关节功能和生活质量的改善可能较好，但目前结果尚不明确。但在住院期间医疗支出上，机器人辅助手术相关费用显著高于传统手术组。研究将继续患者随访，进一步明确两组操作在临床结局、关节功能、生活质量和住院期间医疗支出的差异。

背景

人工关节置换是治疗终末期髋膝关节炎最有效的方法，能够有效解决关节畸形、疼痛和运动受限等问题，从而提升患者的生活质量。(Kim et al. 2020)。其中，机器人辅助手术是髋膝关节置换领域的创新前沿。与传统手术相比，机器人辅助髋膝关节置换存在定位精准度高、精确截骨、个体化置入假体等优势。既往研究提示相比于传统手术，机器人辅助膝关节置换术具有准确辅助截骨、个体化置入假体、更好地保护膝关节周围软组织、减少镇痛药物使用等优势，但也存在手术耗时延长等不足（邵等 2023；Subramanian 等 2019；杨等 2024）。

自2012 年以来，国务院、科技部、工信部、北京市医保局等各部委层面，先

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后有15项重要政策提及“手术机器人发展应用”。2016年发布的《关于促进医药产业健康发展的指导意见》明确指出，要鼓励国产医疗器械技术创新，明确提出发展医用机器人等高端医疗器械。2024年1月18日，工业和信息化部等十七部门联合发布《“机器人+”应用行动实施方案的通知》，提出要加速推进机器人多方面的突破，推动机器人新技术新产品加速应用。2022年，国家医保保障局医药价格和招标采购司发布《“关于征求《关于完善骨科“手术机器人”“3D打印”等辅助操作价格及相关政策的指南（征求意见稿）》意见的函”》，征求定价方案。作为创新性技术，骨科手术机器人正在快速发展中，在其发展过程中应该正该综合平衡合理的支付标准是构建支持手术机器人技术发展和临床应用环境的重要环节，也是引导机器人合理发展、制定相应支持政策的重要环节。

利用接受膝关节转换的真实世界患者数据，研究将对比机器人辅助手术和非机器人手术膝关节转换的临床效果、生活质量和院内医疗成本，致力于明确机器人辅助膝关节置换的成本效果。

一、方法

研究将采用回顾性队列研究，纳入2020.7-2024.3期间因骨关节炎或关节畸形于就诊于积水潭医院矫形骨科，接受机器人辅助或传统全膝关节置换术、ASA评分I-II级、21-80岁的患者。研究排除妊娠期女性患者、膝关节翻修患者、伴有严重的屈曲畸形（＞20°）及严重内外翻畸形（＞20°）、类风湿性关节炎、感染性关节炎的患者。

研究首先通过医疗电子病历确认患者的人口学特征（年龄、性别），确认手术适应症、术前全身疾病等术前特征，并明确手术时长、术中出血和引流量、术后并发症等手术相关指标。研究进一步利用医疗电子病历明确患者入院期间总费用及费用明细（包括手术费、检查费、耗材费、检验费、药品费用和其他）。

研究通过医护人员电话随访患者，明确关节功能评分和生活质量评分。其中关节功能评分采用美国西安大略和麦克马斯特大学骨关节炎指数（The Western Ontario and McMaster Universities Arthritis Index，WOMAC）评分测量。生活质量采用EQ-5D-5L量表测量，并依据已经建立的中国人群效用积分体系（Liu et al. 2014）。此外，医护人员基于电话随访明确患者假体翻修、假体松动、关节相关住院等事件。

统计分析：研究连续性变量呈现形式为平均值（标准差）或中位数（四分位数），分类变量的呈现形式为频数（百分比 ）。研究将使用t检验或卡方检验比较机器人辅

助和传统膝关节置换术两组患者特征上的差异，双侧 $p<0.05$ 定义为有统计学显著差异。

二、初步结果

通过前期数据清理，研究纳入机器人辅助全膝关节置换手术患者 281 例，以 1：1 匹配年龄（±3 岁）、性别、手术日期（±60 天）和患侧，纳入 281 例接受非机器人辅助全膝关节置换手术患者。在匹配后，机器人辅助手术与非机器人辅助手术年龄和性别分布几乎完全一致（机器人辅助手术组平均年龄为 67.33 ［6.86］岁；非机器人手术组为 67.38 ［6.51］岁，表 1）。所有患者术前膝关节疾病诊断均为骨关节炎，其中 52.67% 的患者为左侧关节置换。两组患者在体重指数（BMI）、心脑血管疾病、糖尿病、美国麻醉学会（ASA）评分均无显著性差异（所有变量统计检测 $p>0.05$）

我们观察到两组操作在手术相关指标上有显著差异。在手术时长时，机器人组平均手术时长为 97.56（21.25）分钟，而非机器人组为 79.05（19.54）分钟，机器人手术组手术时长远高于非机器人组（$p<0.001$）。而在术中引流量上，大部分患者术中引流量均较少，故研究初步以是否有引流作为结局指标。研究观察到，机器人术中引流的比例远低于非机器人组（1.42% VS. 9.25,$p<0.001$）。两组患者在术中出血量上无显著差异。

基于完成电话随访的 43 对患者，患者随访时间中位数为 15.01 (9.78， 22.35) 月，机器人组和传统手术组无显著差异（表 2）。两组患者均未观测到任何假体翻修、假体松动或假体感染事件。在机器人手术组，有 1 例患者在出院后发生关节相关住院和关节相关手术，传统手术组未观察到相关事件。在关节相关门诊就诊上，机器人组有 3 例（6.98%）而传统手术组有 2 例（4.65%）。

在关节功能和生活质量评分上，随访时，两组患者对关节满意度、WOMAC 评分、EQ-5D 健康评分和转换后的质量调整生命年（QALYs）上无显著差异（表 3）。相比于传统手术组，机器人辅助手术组 WOMAC 评分和 EQ-5D-5L 总体健康评分改善（即术前-随访的评分差值）可能较高，但差异无统计学差异。

在患者住院期间费用上，相比于传统手术组，机器人手术组的住院总费用（47，634 元 VS. 40，750 元）、手术费用（10，972VS.4813 元）和药品费用（2905 VS. 2481 元）较高（三组比较 $p<0.05$，表 4）。 在其他费用上，两组患者未发现显著差异。

三、初步小结

经过初步数据分析和部分患者随访，目前研究提示相比于传统手术，机器人辅助全膝关节转换有可能在改善关节功能和生活质量上有优势，与临床患者的反馈一

致。但目前随访样本较少，尚不能得到明确结论。但机器人辅助膝关节置换住院支出，特别是手术费用显著高于传统手术。

研究将继续完成患者随访，进一步明确机器人辅助手术对关节功能、生命质量以及医疗支出的影响。同时，研究将进行亚组分析，探索不同年龄、关节病严重程度的患者中，机器人与传统手术对以上结局指标的影响。

表1.匹配后机器人辅助组和传统手术组的患者特征

	机器人辅助组（n=281）	传统手术组（n=281）	P 值
年龄，岁	67.33 (6.86)	67.38 (6.51)	0.38
性别，女	230 (81.85)	230 (81.85)	/
膝关节骨关节炎	281 (100)	281 (100)	/
手术年份，2022年以后	147 (52.31)	142 (50.53)	0.74
术侧，左侧	148 (52.67)	148 (52.67)	/
BMI, kg/m^2	28.94 (10.93)	26.68 (3.86)	0.068
心脑血管疾病	156（55.52）	136 48.40)	0.11
糖尿病	50 (17.79)	48 (17.08)	0.91
ASA 1级	93 (33.10)	106 (37.72)	0.33

ASA, American Society of Anesthesiologists.

表2.部分随访患者的临床结局

	机器人辅助组（n=43）	传统手术组（n=43）	P 值
术后时间，月	14.90 (9.85, 21.87)	15.13(8.88, 22.43)	0.86
假体翻修	0	0	
假体松动	0	0	
假体感染	0	0	
关节相关住院	1 （2.33）	0	
关节相关手术	1 （2.33）	0	
关节相关门诊就诊	3 （6.98）	2 （4.65）	0.79

表3.部分随访患者的健康结局

	机器人辅助组（n=43）	传统手术组（n=43）	P 值
随访关节满意度，非常满意	29 (67.44)	30 (69.77)	0.55
WOMAC评分			
术前	53.19 (23.88)	48.56 (22.54)	0.36
随访	5.09 (7.07)	6.79 (11.71)	0.42
术前-随访差值	48.09 (22.96)	41.77 (22.08)	0.20
ED-5D-5L健康评分-术前			
术前	53.69 (16.12)	55.70 (12.84)	0.53
随访	86.71 (10.49)	86.28 (11.40)	0.86
随访与术前差值	33.02 (17.73)	30.58 (14.20)	0.49
QALYs	0.95 (0.47)	0.90 (0.42)	0.63

QALYs,质量调整生命年

表4.部分随访患者住院期间医疗支出

	机器人辅助组（n=43）	传统手术组 （n=43）	P 值
住院总费用，元	39520 (34417,61589)	41329 (28042,51123)	0.15
手术费用，元	10376 (10376,14409)	4838 (2376, 6409)	<0.001
检查费，元	674.4 (410.8, 1073.0)	802.9 (314.4, 1574.9)	0.99
耗材费，元	20596 (14471, 41737)	29025(17140, 39287)	0.50
检验费，元	387 (305, 1257)	1361 (207, 1699)	0.84
药品费用，元	2758 (2109, 3366)	2209 (18157, 2983)	0.026
其他费用，元	67 (4, 67)	45 (4, 67)	0.35

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人工智能与外科职业壁垒：研究进展

潘聿航 易君健 周清源*

摘　要　本文探究手术机器人引入对于外科性别比例的影响。在本次报告中，我们总结了数据来源，基准回归模型，稳健性检验，异质性分析以及机制检验方法。

1. 基准结果

在本节中，我们展示了主要研究结果，分析了达芬奇机器人引入对外科科室性别构成的影响。

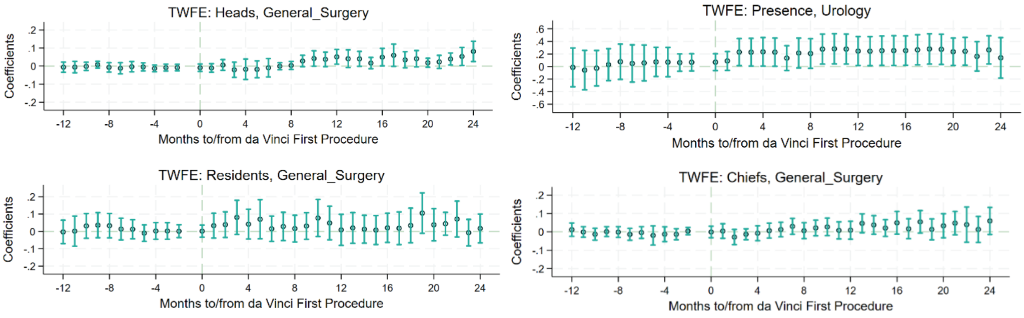

图1 距离首次使用达芬奇机器人手术的月份与女性比例

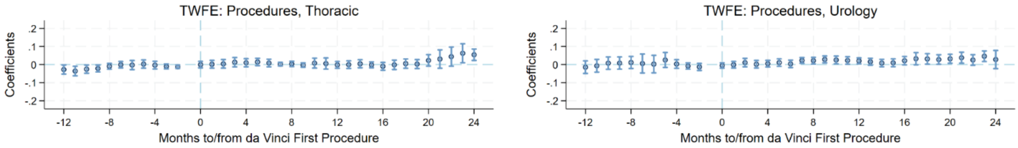

图2 距离首次使用达芬奇机器人手术的月份与女性工作量

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图 1 展示了各科室中女性比例以及女性科主任、主任医师、主治医师和住院医师的比例随时间的变化情况。我们将机器人引入前一个月的处理组和对照组的医院科室的差异作为参考基准。研究发现，在达芬奇手术系统引入后，女性相对比例在泌尿外科和普通外科有所上升，而在其他科室则相对保持稳定。此外，在普通外科中，女性科主任和主任医师的比例有所增加，这表明女性获得了更多的晋升机会。然而，这些变化并未在机器人引入后立即发生，可能是因为科室需要时间进行人员调整。

图 2 展示了不同科室中女性手术量的变化趋势。结果显示，技术引入后，胸外科和泌尿外科中由女性外科医生执行的手术量有所增加。这表明技能偏向型技术变革可能改变了男女之间的比较优势，从而促进了女性更多进入外科领域。

2. 研究进展

上一节的证据表明，某些科室中女性的比例和晋升机会有所增加。本节探讨与这一性别差距缩小相关的机制。具体而言，我们采用病例层面和医生层面数据，估计达芬奇机器人的引入对医生在资源使用决策和患者健康结果的分性别影响。

2.1 病例层面证据：分性别生产率

结果变量 为了测度医疗资源的使用情况，我们包括了三个主要结果变量：(i) 患者住院时间，(ii) 用于患者检查和检测的费用，以及 (iii) 本次住院期间的总医疗费用。为了减小极端值的影响，我们对医疗支出取对数。为了测度医疗质量，我们考察了两个主要的患者结果：(i) 患者 30 天内再次住院的指标——即患者在出院后 30 天内是否再次入院，以及 (ii) 患者是否在院内死亡的指标。

控制变量 我们的模型还包括一组患者控制变量，包括患者年龄段，性别，以及主要诊断的 ICD-10（国际疾病分类，第十版）三位代码。

我们的实证模型如下：

$$Y_{ijt} = \sum_{k=-12,\, k\neq -1}^{k=24} \beta_k MR_{jt,k} + X_i\gamma + \delta_j + \eta_t + \epsilon_{jt} \#(1)$$

其中， Y_{ijt} 表示病例 i 在年份－月份 t，医院科室 j 中的医疗资源使用和医疗质量的测度。 t．$MR_{jt,k}$ 是虚拟变量，当年份－月份 t 距离医院科室 j 首次开展机器人辅助手术的时间为前（后）k 个月时取值为 1，否则为 0。X_i 表示患者风险调整因素。

我们还加入了医院科室固定效应 δ_j 和年份－月份固定效应 η_t. ϵ_{jt} 。是随机误差项。我们将标准误聚类在医院科室层面。

2.2 医生层面证据：分性别生产率

为探究机器人技术引入后女性外科医生获得更多晋升机会的原因，我们分别考察了机器人技术对男性和女性医生生产率的影响程度。

我们采用如下实证模型来估计医生使用机器人对其生产率和工作量影响的因果关系：

$$Y_{it} = \sum_{k=-12,\, k\neq -1}^{k=24} \beta_k MR_{it,k} + \delta_i + \eta_t + \epsilon_{it} \#(2)$$

其中，下标 i 表示医生，t 表示年份－季度。因变量 Y_{it} 代表医生 i 在 t 时期的患者院内死亡率、30 天内再入院率、平均住院天数和平均医疗费用，以及医生 i 在 t 时期实施的手术总数。我们关注的自变量 $MR_{it,k}$ 是虚拟变量，当年份－季度 t 距离医生 i 首次使用达芬奇手术机器人的时间为前（后）k 个季度时取值为 1，否则为 0。我们引入医生固定效应 δ_i 以控制医生间的异质性，即方程（2）的估计利用了医生个体内部的差异。最后，为误差项。标准误在医生层面进行聚类。

机器人手术是否有助于降低胰腺恶性肿瘤的疾病经济负担？一项微观成本研究

石茵 武子婷*

摘　　要　通过文献综述，总结机器人手术与腹腔镜或开放手术治疗胰腺恶性肿瘤的有效性相关的现有研究的主要结果和结论，以及该领域尚未解决的问题。主要结果和结论为：腹腔镜手术对比开腹手术，在围手术期安全性方面有优势，但在肿瘤学获益方面优势不明显；机器人手术对比开腹手术，在围手术期安全性方面有优势，但在肿瘤学指标方面，机器人手术治疗胰头癌存在一定优势，治疗胰体尾癌则无明显优势；机器人手术和腹腔镜手术在围手术期安全性和肿瘤学指标方面的对比有待大样本研究提供支持，同时，应考虑学习曲线对机器人手术效果的影响。为了验证这些主张，需要进行更广泛的研究，并采用标准化方法，同时关注发展中国家的大规模研究和长期效果；外科医生的学习曲线及胰腺恶性肿瘤的亚型对全面评估机器人手术的有效性和成本至关重要。此外，我们还将对本研究将采用的统计分析方法进行详细汇报，并计划在数据获取后据此进行数据分析。

一、背景

1994年世界首例腹腔镜胰十二指肠切除术（laparoscopic pancreatoduodenectomy，LPD）被报道以来，腹腔镜或机器人辅助技术应用于胰腺外科的探索一直在进行(Shah and Singh 2024)。当前，腹腔镜或机器人辅助手术应用于胰腺癌根治性治疗方面的争议焦点主要集中于治疗效果的肿瘤学评价与手术安全性等方面。关于腹腔镜或机器人辅助胰腺癌根治术，中国专家在2022年版的共识中讨论了其疗效和安全性，认为微创根治术具有广阔的应用前景(Study Group of Minimally Invasive Treatment for Pancreatic Cancer in China Anti-Cancer Association and Chinese Pancreatic Surgery Association 2023)，但需要强调较长时间的学习曲线(Pancreatic Cancer Committee of Chinese Anti-cancer Association 2021)。

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本次进展分为两个部分，一是研究背景中机器人对比腔镜和开腹手术治疗胰腺癌的效果评价方面的文献综述，以补充上次进展中的机器人对比腔镜和开腹手术治疗胰腺癌的成本或成本效果／效用研究的文献结果；二是对本研究将采用的统计分析方法进行详细汇报，并计划在数据获取后据此进行数据分析。

二、方法

1. 文献综述

研究人员通过检索PubMed中收录的文献获取研究所需信息。本研究使用了三组检索词，其一为“胰腺”和“胰腺”与“癌症”、“腺癌”和“癌症”，其二为“机器人”和“外科手术”，将上述检索词以以“AND”逻辑链接获得健康效果主题结果。检索过程未限制语言。本研究纳入了2011年1月1日至2024年5月30日期间最相关的临床试验、系统综述和荟萃分析、其他原创研究文章和指南，由两名研究人员筛选和总结文献关键信息。

2. 统计分析方法

A. 所有样本的个人基本信息描述及时间分布（分三种术式）。

B. 本研究时限未超过1年，故无需对成本进行贴现。对于回顾性收集的发生在过去的费用，为了反映通货膨胀或紧缩情况，通过居民消费价格指数（consumer price index，CPI）转换为2023年的成本。

C. 抽取240人，并描述样本的个人基本信息描述及时间分布（分三种术式）。

D. 首先用240人的调研结果构建各类无法观测的成本的预测模型，再外推至所有样本，如此研究期间的所有样本都将获得住院及出院30天内的直接医疗费用、直接非医疗费用、间接成本。

1) 首先，采用Cox回归模型构建胰腺恶性肿瘤患者出院后生存情况及其影响因素之间的相关关系。使用Lasso方法估计Cox回归的系数，标准的Cox回归模型可能因为数据的高维度和复杂性而面临过拟合的风险，而Lasso回归通过将一些不重要的回归系数收缩至零，实现了特征的选择，从而提高了模型的预测能力和解释性。具体模型如下：

$$\lambda(t) = \lambda_0(t)\exp^{\beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n}$$

其中：$\lambda(t)$ 是时间t处的风险函数，t的单位为天；$\lambda_0(t)$是基准风险

函数，即样本的平均风险函数，表示在所有协变量（$x_1 \sim x_n$）都为零的情况下的风险；$\beta_1 \sim \beta_n$ 是协变量 $x_1 \sim x_n$ 的回归系数，用于表示每个协变量对胰腺恶性肿瘤患者出院后死亡的相对影响，本研究中，协变量包括性别、年龄、民族、医疗保险类型、婚姻状况、家庭常住地（城市／县／乡镇／农村）、临床分期、年龄校正 Charlson 合并症指数、手术术式（机器人／腹腔镜／开腹）、手术时长、术中出血量、术者经验（术者此前完成该手术术式例数）。

2) 根据上述模型，预测每个个体的生存时间 t（单位：天）
3) 在生存模型基础上，构建生存时间 t 与直接非医疗成本和间接成本的预测模型，具体如下：

$$\mathrm{Cost}_{\mathrm{non-med-in}hosp} = \mathrm{Cost}_{\mathrm{med}} + x_1 + \ldots + x_n + \mathrm{LOS}$$

$$\mathrm{Cost}_{\mathrm{non-med-out}hosp}/t = \mathrm{Cost}_{\mathrm{med}} + x_1 + \ldots + x_n$$

式中，$\mathrm{Cost}_{\mathrm{indirect-in}hosp}$ 为住院期间直接非医疗成本；$\mathrm{Cost}_{\mathrm{non-med-out}hosp}/t$ 为出院后每日直接非医疗成本；$x_1 \sim x_n$ 为手术术式（机器人／腹腔镜／开腹）、性别、年龄、民族、医疗保险类型、婚姻状况、家庭常住地（城市／县／乡镇／农村）、临床分期、年龄校正 Charlson 合并症指数、手术时长、术中出血量、术者经验（术者此前完成该手术术式例数）；LOS 为住院时长。

$$\mathrm{Cost}_{\mathrm{indirect-in}hosp} = \mathrm{Cost}_{\mathrm{med}} + x_1 + \ldots + x_n + \mathrm{LOS}$$

$$\mathrm{Cost}_{\mathrm{indirect-out}hosp} = \mathrm{Cost}_{\mathrm{med}} + x_1 + \ldots + x_n$$

式中，$\mathrm{Cost}_{\mathrm{indirect-in}hosp}$ 为住院期间间接成本；$\mathrm{Cost}_{\mathrm{indirect-out}hosp}$ 为院外间接成本；$x_1 \sim x_n$ 为手术术式（机器人／腹腔镜／开腹）、性别、年龄、民族、医疗保险类型、婚姻状况、家庭常住地（城市／县／乡镇／农村）、临床分期、年龄校正 Charlson 合并症指数、手术时长、术中出血量、术者经验（术者此前完成该手术术式例数）；LOS 为住院时长。

4) 用所构建的直接非医疗成本和间接成本预测模型预测大样本在住院期间（含出院当天）和出院 30 天内的相关成本信息。

E. 定量指标的描述将计算例数 (N)、均数 (Mean)、标均差 (SD)、中位数 (Median)、最小值 (Min) 和最大值 (Max)，使用 Kruskal-Wallis test for nonnormally distributed variables; T-test for normally distributed variables。分类变量以

数字和百分比表示，并使用$\chi2$检验进行比较。

F. 使用逆概率加权逻辑回归模型对基线患者特征的差异进行调整加权（Inverse probability of treatment weighting，IPTW），对可观测的混杂因素如入组患者的人口社会经济特征、疾病相关指标以及术者特征进行控制。

1) 建立逻辑回归模型：根据个体的特征（如人口社会经济特征、疾病相关指标、术者特征等）以及是否接受治疗／暴露的状态，建立一个逻辑回归模型，来预测每个个体接受某项治疗的概率。

2) 计算权重：使用逻辑回归模型估计每个个体接受治疗的概率P(Treament | X)，其中 X 表示个体特征。接着，计算个体的权重：对于接受治疗的个体，权重为1/P(Treatment | X)。

3) 加权回归分析：在得到权重wi后，使用最小二乘回归或广义线性模型（GLM）对观测数据进行重新加权分析，应用加权数据来估计因果效应，从而减少混杂因素的影响。

4) 灵敏性分析：为了检验结果是否对模型假设敏感，需进行灵敏性分析。通过不同的模型设定或不同的假设检验，确保结果的稳健性和可靠性。

G. 选择基于Gamma分布的广义线性模型评价机器人手术对直接医疗成本及其中各类子费用、直接非医疗成本、间接成本的影响。

$$\log(\mathrm{Y}) = \beta_0 + \sum_{j=1}^{J} \beta_j \mathrm{comorbidity}_j + \varepsilon$$

式中，Y为直接医疗成本／直接非医疗成本／间接成本，j指代该患者的第j种共患疾病（可以有1～J种共患疾病）。

$$\mathrm{AF}_j = p_j(e^{\beta_j} - 1)$$

式中，为总费用中归因于共患疾病j的比例，为样本中目标疾病和共患疾病同时发生的概率，=0.006时，意为总费用的0.6%归因于共患疾病j。

总费用中，归因于各类共患疾病的总费用为记为outflow，计算如下

$$\mathrm{outflow} = \text{total expenditure of 目标疾病} * \sum_{i} \mathrm{AF}_j$$

由于胰腺癌造成的费用计算如下：

$$\text{Adjusted total expenditure of 目标疾病} = \text{total expenditure of 目标疾病} - \text{outflow}$$

运用广义线性模型(GLM)评价机器人手术对费用水平的影响,费用服从伽马分布, $\text{Adjusted total expenditure}_i$ 为个体 i 的费用，X_i 为一系列影响因素（手术术式（机器人／腹腔镜／开腹）、性别、年龄、民族、医疗保险类型、婚姻状况、家庭常住地（城市／县／乡镇／农村）、临床分期、年龄校正 Charlson 合并症指数、手术时长、术中出血量、术者经验（术者此前完成该手术术式例数）），ε_i 为误差项。

$$\log(\text{Adjusted total expenditure}_i) = \beta_0 + \beta X_i + \varepsilon_i$$

H. 针对不同病种、主刀医生是否过学习曲线进行亚组分析（执行上一步中的广义线性模型）。

三、结果

（一）机器人对比腔镜和开腹手术治疗胰腺癌的效果评价文献综述

1. *现有研究多为对比腹腔镜手术，或以腹腔镜手术为主的微创手术方式和开腹手术之间的效果差异。总结而言，腹腔镜手术在围手术期安全性方面有优势，但在肿瘤学获益方面优势不明显。*腹腔镜手术治疗胰头癌和胰体尾癌的围手术期部分安全性指标优于开腹手术，但在术后90天病死率方面无优势。针对胰头癌和胰体尾癌，LPD的总手术时间略长于开腹胰十二指肠切除术（open pancreatoduodenectomy, OPD）(Kuesters et al. 2018; Stauffer et al. 2017; Zhou et al. 2019; Feng et al. 2021)。LPD在住院时间与术中出血量方面优于OPD，在术后并发症如胰瘘、术后出血及围手术期病死率等方面的差异则无统计学意义 (Feng et al. 2021; Jiang, Zhang, and Zhou 2019; Yin, Jian, Hou, and Jin 2019)。Chapman等(Chapman et al. 2018)对美国癌症数据库（National Cancer Database, NCDB）中75岁以上胰头癌患者接受LPD与OPD的90 天病死率进行分析，发现老年LPD患者的病死率低于OPD。而对NCDB中大样本胰体尾癌病例资料的回顾性研究结果则提示，LDP与ODP在90 天病死率方面两者差异无统计学意义 (Kantor et al. 2017)。

*腹腔镜手术治疗胰头癌的肿瘤学获益不明确，未发现治疗胰体尾癌的肿瘤学获益。*对于胰头癌，LPD在R0切除率，淋巴结获取数量，以及术后辅助化疗开始时间方面优于OPD(Jiang, Zhang, and Zhou 2019; Yin, Jian, Hou, and Jin 2019; Feng et al. 2021; Peng et al. 2019)；但另一项研究未发现LPD和OPD在上述结局指标方面的差异 (Chen et al. 2020)。但两种手术方式术后接受辅助化疗比

例的差异无统计学意义 (Chen et al. 2020；Peng et al. 2019)。针对胰头癌 LPD 术后长期生存情况的 Meta 分析结果显示，LPD 的无病生存期长于 OPD(Peng et al. 2019；Chen et al. 2020)；但亦有文献认为两者总体生存（overall survival，OS）的差异无统计学意义 (Zhou et al. 2019；Feng et al. 2021)。对于胰体尾癌，LDP 与 ODP 在 R0 切除率 (Ricci et al. 2015；Riviere et al. 2016；Gavriilidis，Roberts，and Sutcliffe 2018) 与清扫淋巴结数量 (Gavriilidis，Roberts，and Sutcliffe 2018；Ricci et al. 2015) 方面的差异无统计学意义。对远期生存情况而言，癌患者接受 LDP 或 ODP 后，化疗完成率、术后复发率及总体生存期的差异均无统计学意义 (Ricci et al. 2015)。

2. *较少的研究对比了机器人和开放手术之间的差异，发现机器人手术在围手术期安全性方面有优势，但在肿瘤学指标方面，机器人手术治疗胰头癌存在一定优势，治疗胰体尾癌则无明显优势。*机器人手术治疗胰头癌和胰体尾癌的围手术期部分安全性指标优于开腹手术。基于中国人群的一项多中心随机对照试验结果表明机器人手术在缩短住院时长方面优于开腹手术 (Liu et al. 2024)。Vining 等 (Vining et al. 2020) 对美国外科医师协会 - 国家手术质量改进计划（American College of Surgeons-National Surgical Quality Improvement Program，ACS-NSQIP）中胰头癌数据进行倾向性得分匹配（Propensity Score-Matched，PSM）分析，结果显示，RPD 组术后出血发生率低于 OPD 组，而在术后胰瘘方面差异无统计学意义。另两篇单中心的小样本 PSM 研究结果亦得到类似结论 (Kauffmann et al. 2019；Baimas-George et al. 2020)。Nassour 等 (Nassour et al. 2020) 在研究中分别纳入 332 例和 2 386 例接受 RDP 和 ODP 治疗的胰体尾癌患者资料，结果显示，RDP 的住院时间和 90 天病死率方面优于 ODP。

机器人手术治疗胰头癌的部分肿瘤学指标优于开腹手术，机器人手术治疗胰体尾癌的肿瘤学优势尚存在争议。Nassour 等 (Nassour et al. 2020) 对 NCDB 中的数据进行分析，发现 RPD 组在淋巴结获取数量与术后辅助化疗率方面优于 OPD 组，在 R0 切除率与术后生存期方面的差异无统计学意义。两个单中心的 PSM 分析亦得到类似结论 (Kauffmann et al. 2019；Baimas-George et al. 2020)。另有研究者认为，接受 RPD 的胰头癌患者较 OPD 能在术后更早地接受辅助化疗 (Boggi et al. 2016)。有研究显示，RDP 在淋巴结清扫数量与术后辅助化疗率方面优于 ODP，而在 R0 切除率方面差异无统计学意义 (Nassour et al. 2020)，但也有研究则未发现两者在淋巴结清扫数量与 R0 切除率方面的差异 (Lee et al. 2015)。

3. *机器人手术和腹腔镜手术之间的差异调查比较少，基于相关研究，我们发现*

*机器人手术和腹腔镜手术在围手术期安全性和肿瘤学指标方面的对比有待大样本研究提供支持，同时，应考虑学习曲线对机器人手术效果的影响。*机器人手术治疗胰头癌和胰体尾癌在围手术期指标方面的优势有待大样本研究证实。对于胰头癌，基于我国2255例样本人群的一项多中心回顾性研究表明（Zhang et al. 2023），机器人手术有助于缩短手术时间，降低术中出血量和中转开腹率，其他指标无明显优势。其余研究结果表明，RPD较LPD的中转开腹率低（Stiles et al. 2018；Kamarajah et al. 2020），同时可降低术中输血率（Kamarajah et al. 2020），其他围手术期安全性指标方面两者无区别（Kamarajah et al. 2020；Stiles et al. 2018）。然而，该研究结果为基于20例左右接受了RPD的患者所得，因此仅代表了学习曲线早期阶段的安全性数据。针对胰体尾癌病例，回顾性分析发现RDP的中转开腹率低于LDP，但住院时间与90 天病死率的差异无统计学意义（Watson et al. 2020；Raoof et al. 2018）。

机器人手术治疗胰头癌的肿瘤学指标优势均不明显，机器人手术治疗胰体尾癌的多数肿瘤学指标优势均不明显或存在有争议的结果。RPD与LPD在胰头癌R0切除率、清扫淋巴结数量、术后辅助化疗率、OS，以及1、2、3年的生存率方面的差异均无统计学意义（Nassour et al. 2020；Wehrle et al. 2024）。针对胰体尾癌，RDP与LDP在R0切除率、淋巴结获取数量、术后接受辅助化疗时间及辅助化疗率方面的差异无统计学意义（Raoof et al. 2018）。Watson等（Watson et al. 2020）对NCDB中胰体尾癌病例资料的分析结果中，除RDP在淋巴结获取数量方面优于LDP外，其他肿瘤学指标方面则无优势。从长期生存结果看，除Watson等（Watson et al. 2020）报告RDP的OS优于LDP外，其他研究均未发现两者在OS和1、2、3年生存率方面的差异有统计学意义（Raoof et al. 2018；Baimas-George et al. 2020；Daouadi et al. 2013）。

（二）研究数据获取进度

1. 通过问卷调查方法获取直接非医疗成本和间接成本，目前已完成17份合格问卷的收集，问卷收集具体方式如下：

· 由301医院病房管床护士负责收集问卷信息。

· 已开始收集9月2日起出院的胰腺恶性肿瘤患者，接受了胰腺切除手术的即可纳入，机器人、腹腔镜、开腹各80例。

患者或家属填写均可。

· 为保证所收集信息的准确性和尽量减少对患者和临床的打扰，经与临床医生沟通，题目简单易懂，数量较少。

2. 通过院内数据抄录方式获取医疗成本，目前已根据术式关键词在医院系统中共筛选出12166例于2014.1.1-2024.9.12接受了机器人/腹腔镜/开腹胰腺切除术的患者，结合诊断，进一步筛选其中的胰腺恶性肿瘤病例4713例，未来将继续筛选诊断为壶腹部位恶性肿瘤的患者中确诊为胰腺恶性肿瘤的病例。目前已完成600例胰腺恶性肿瘤患者的信息抄录。

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我国高科技医疗技术分布的公平性分析：手术机器人的证据

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摘　要　在经济快速发展的背景下，人民的卫生服务需求日益增长，呈现出高层次、多样化的局面，我国卫生公平面临严峻挑战。本研究通过手术机器人这一高科技医疗设备在中国分布的公平性，为文献相关监管政策提供了实证基础。本研究采用基尼系数（洛伦兹曲线）、泰尔指数和空间自相关等方法展示了我国及东、中、西部地区手术机器人分布的公平性和聚集性。结果显示，我国手术机器人的配置公平性逐年增加，人口分布的公平性优于地理面积配置的公平性；东中西部呈现差异化分布，中部地区的公平性最优，东区地区虽然资源配置量相对较高，但区域内的公平性亟待加强，区域内的差异比重逐年增加；技术的分布具有空间聚集性，同时存在聚集的异常点，提示技术资源优化的锚点。

一、背景

从1978年的“阿拉木图宣言”提出“2000年人人享有初级卫生保健”到2015年的联合国特别峰会提出“2030年实现可持续发展目标”（其中包括保障“全民全生命期健康”），国际社会始终倡导的一个核心理念即人人公平地享有健康 (United Nations 2015)。自1978年，我国开始以市场为导向的经济改革后，我国为实现全民健康覆盖作出众多实质性的努力，特别是基本医疗保险和基本公共卫生服务的全民覆盖 (Tang et al. 2008)。习近平总书记曾多次谈及健康公平问题，指出让广大人民群众享有公平可及、系统连续的预防、治疗、康复、健康促进等健康服务 (the Xinhua News Agency 2024)。

因此，“健康公平”的概念越来越受到关注。虽然已发表的研究报告了我国国家层面健康状况 (Zhang and Kanbur 2005；Tang et al. 2008)、卫生保健服务 (National Health Commission 2021；Tang et al. 2008)、医疗保险 (Yang et al. 2021)、卫生资源（包括专业卫生人员）(Liu et al. 2016) 等方面的不公平，但只有少数研究关注到高新技术医疗设备分布的公平性。特别地，我国关于两项常见高新医疗技术设备（计算机断层扫描即CT和磁共振成像即MRI）的研究发现，在2004年之前，我国这两项技术在全国的分配相对公平，而2006年之后的研究结果却显示，高新技术设备的公平性较低，且其分布与地区社会经济水平显著相关 (He, Yu, and

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Chen 2013)。虽然我国在基本卫生服务的全民覆盖上实现了重大突破，但是优质资源的集中化始终难以避免。2024年，中共中央发布《关于进一步全面深化改革 推进中国式现代化的决定》，强调深化医药卫生体制改革应“促进优质医疗资源扩容下沉和区域均衡布局”(the Central Committee of the Communist Party of China 2024)。手术机器人作为目前高精尖前沿医疗卫生技术的代表之一，自2006年首例达芬奇手术机器人引入我国以来，基于技术效果优势和社会效益等因素，手术机器人在我国的扩散得到了蓬勃的发展，然而，我国仍在手术机器人技术扩散的早期。研究表明，自2000年手术机器人问世，截至2015年美国超过50%的医院配备有手术机器人并展开手术，但我国自首次使用手术机器人以来，截至2021，同样经历了15年的时间，仅有224家医疗机构配备手术机器人，占全国医院数量的0.61%，可以预见技术仍有较大的市场空间。目前，美国(Mohanty et al. 2022)、瑞士(Stalder et al. 2024)、澳大利亚和新西兰(Royal Australasian College of Surgeons 2021)等发达国家探讨了手术机器人分布的不公平性，发现在机构的专业程度、区域的经济水平和类型等因素中呈现差异，中国还缺乏相关的实证研究。因此，本研究通过探究手术机器人这一高科技医疗设备在中国分布的公平性，为文献和相关监管政策提供实证证据和基础。

二、方法

本研究以我国手术机器人人的引入和使用作为研究对象，数据来源于作为目前手术机器人的市场份额绝对优势（占中国大陆部分类别手术机器人业务量90%以上）的机器人服务商的经营数据。常住人口数据来源于《中国统计年鉴》，各省（自治区、直辖市）的地理面积来源于各省统计年鉴。按照国家统计局的地区分组，将我国除台湾省、香港和澳门特别行政区以外的31个省、自治区、直辖市划分为东部（北京、天津、河北、山东、辽宁、上海、江苏、浙江、福建、广东和海南共11个省份）；中部（山西、吉林、黑龙江、安徽、江西、河南、湖北和湖南共8个省份）和西部（内蒙古、广西、重庆、四川、贵州、云南、西藏、陕西、甘肃、青海、宁夏和新疆共12个省份）3个区域。

本研究主要采用基尼系数（洛伦兹曲线）、泰尔指数和空间自相关分析探索手术机器人技术设备采用（技术设备的购买配置）的公平性。基尼系数常用来衡量某项社会资源的分配差距，学者们常将其引入卫生健康领域，用于评价卫生资源配置的公平性(Berndt et al. 2003)，基尼系数的取值范围为0～1参考国际惯例，将0.4作为分配差距的“警戒线”，<0.2表示绝对公平，0.2-0.3表示相对公平，

0.3-0.4 表示正常情况，0.4-0.6 表示相对不公平，>0.6 表示高度不公平 (JIN et al. 2015)。Theil 指数的取值范围为 0~1，数值越小，资源分配越公平，同时，泰尔指数可进一步计算不同区域内部和之间的差异，展示不公平的主要来源 (Theil 1967)。进一步地，采用全局 Moran’s I 指数从整体分析我国手术机器人的空间自相关性及其变化趋势，Moran’s I 指数的取值一般为 [-1,1]，<0 表示地区间的技术设备资源为空间负相关，等于 0 表示为随机分布，>0 表示为空间正相关，局部 Moran’s I 用于识别特定位置及其邻域的空间自相关性，可识别热点（高值聚集区）、冷点（低值聚集区）或异常值（高－低聚集或低－高聚集）等局部模式 (Mathur 2015)。医疗机构的标准地址收集于各由各机构官方网站查询，经纬度坐标使用高德开放平台进行转换。本研究的数据分析和作图软件为 R 4.2.3。

三、结果

Table S1 展示了 31 个省市的人口经济学特征及手术机器人的拥有量，可见截止 2022 年中，四个直辖市（北京、上海、天津和重庆）拥有更高的人均手术机器人量，最高的是北京（1327.84/ 十亿人），虽然广东省拥有较多的设备数量（21 台），但人均的机器人数量仅名列中游，而西藏还未实施一台机器人辅助的手术。Figure 1 显示了我国 示手术机器人的绝对数 高指主要集中在东部沿 高值，但是整体而言，

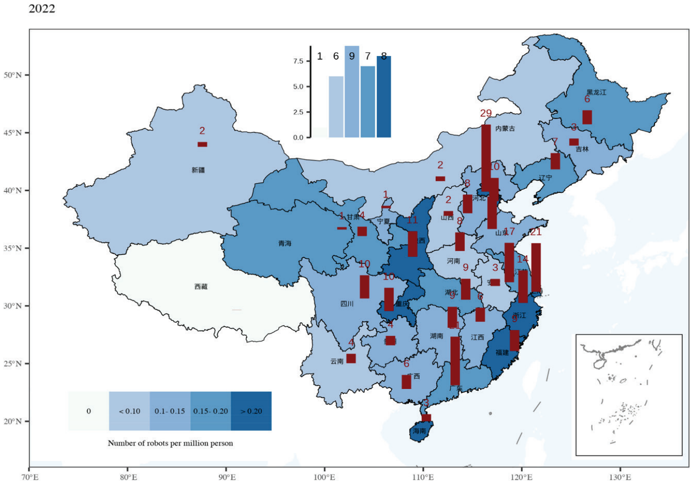

Figure 1. The Distribution of Surgical Robots In China

Notes: The red bar graph indicates the number of surgical robots, and the depth of color of the map indicates the number of surgical robots per capita.

Figure 2的左图展示了按人口分布的洛伦兹曲线和2007-2022年基尼系数的变化趋势。洛伦兹曲线的颜色越深表示年份越新，可见随着时间推移，各省份间的技术资源配置呈现出越发公平的趋势，基尼系数显示我国的手术机器人的配置在早期整体相对不公平，但晚期公平性增高，到2021和2022年达到了一个比较公平的状态。右图则展示了按照地理面积累积计算的洛伦兹曲线和基尼系数，整体的变化趋势与人口计算的结果一致，但可见按照面积分布的技术配置相对于人口配置更不公平。

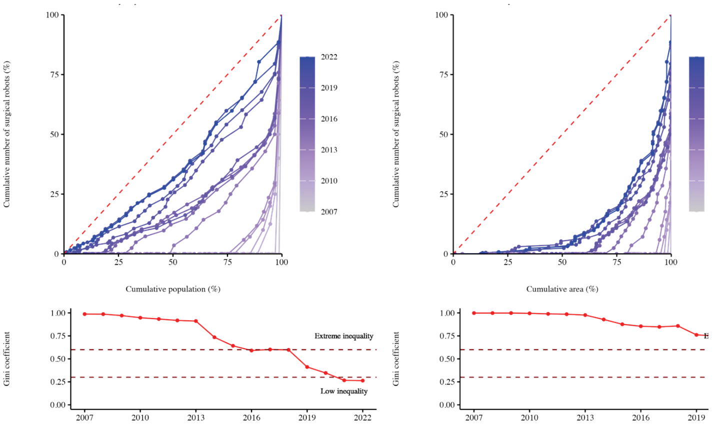

Figure 2. Lorenz Curve and Trend of Gini coefficient of Surgical Robots In China

Figure 3展示了我国东、中、西部地区的技术配置公平性以及和全国水平的对比，左图展示了按人口分布的基尼系数，可见整体而言，中部地区的公平性相对较高，东部地区虽然普遍技术配置较多，但公平性还有待提高。随着时间推移，各省份间的技术资源配置呈现出越发公平的趋势，到2021和2022年基本都达到了一个比较公平的状态。右图则展示了按照地理面积累积计算基尼系数，整体的变化趋势与人口计算的结果一致，仍然是中部地区相对更公平，其次是东部地区，不公平性的降低速率较快，而西部地区仍然与全国的水平相对一致，且直到2022年，仍呈现出高度的不公平性，我国西部地区相对而言往往地广人稀，在考虑资源配置时应更注意地理空间的可及性。

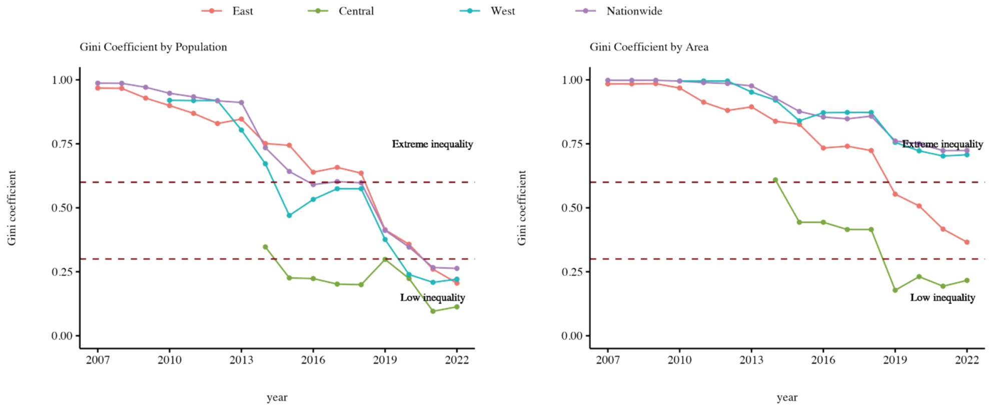

Figure 3. Trend of Gini coefficient of Surgical Robots In Different Area

Table 1 展示了我国 2014-2022 年手术机器人配置的泰尔指数，以及分为东、中、西部区域内和区域间的差异贡献率（区域内或区域间差异 / 总差异）。可见，随着年份增加总泰尔指数降低，公平性增高。在早年间，区域间的差异占总不公平性差异的主导，最高达 87.9%，但随着中、西部地区逐渐开始采用手术机器人，组间的差异逐渐降低，组内的差异反而占据主导，到 2022 年组内的差异超过一半，占到 52.1%，显示在技术设备配置过程中，还应该注意手术机器人设备资源的相对“冷点”。

Table 1—Theil Indexs and Contribution Percent Between and Within the Area through years

Year	Theil Index	Contribution percent between the area (%)	Contribution percent within the area (%)
2014	0.90	16.65	83.35
2015	0.59	12.10	87.90
2016	0.48	16.50	83.50
2017	0.49	14.02	85.98
2018	0.50	19.62	80.38
2019	0.29	36.45	63.55
2020	0.23	45.65	54.35
2021	0.17	44.50	55.50
2022	0.18	47.91	52.09

以 2022 年为例，本研究进一步进行空间自相关分析，结果显示我国手术机器人全局 Moran ‘s I 指数为 0.11，$P< 0.05$，存在显著空间正相关，呈空间聚集分布。Figure S1 显示了局部自相关结果结果，可见天津、上海和新疆区域呈现出显著的空

间聚集性。局部自相关的聚类图（LISA），其中红色代表自身为高值区域并与高值区域相邻（H-H），为天津和四川省；蓝色代表低值区域与低值区域相邻（L-L），为内蒙古，表示内蒙古及其周围地区均为技术资源的缺乏区域；以及异常值，即高值区域被低值区域包围（H-L），及江苏和浙江，则说明与其相邻的安徽和江西等省份可能呈现出相对异常的低值，需要更多公平性层面的关注。

四、总结与进一步计划

在本次分享中，我们简述了手术机器人作为高科技医疗技术的代表，在我国各省、区域间分布的公平性，展示了我国高科技医疗技术采用在区域间的演变历程和现况。目前，相比于欧美、澳大利亚等发达国家，我国手术机器人的技术量和相对量均还十分缺乏，手术机器人的市场空间较大，在技术的大规模普及之前，需加强对技术分布公平性的规划和关注，特别是区域内的差异愈发严峻，聚集分布的异常点提示了客观上的技术缺口，同时技术的先行者可为后采用者提供技术的实证经验，为技术的“适宜”扩散提供因地制宜的证据基础。

目前，本研究对我国达芬奇手术机器人的使用现况和宏、中观影响因素进行了初步的分析（包括公平性分析和市场竞争、规模等机构因素分析），并完成系统的文献证据回顾、部分专家咨询与微观访谈分析，构建了微观影响因素研究的理论框架。接下来本研究将对分布的差异性与公平性进一步剖析，结合进一步的问卷与访谈探索其规律和成因，为我国手术机器人相关研究政策制定提供证据基础。

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