

# Medical Technologies with Comparative Advantages on Different Dimensions: Evidence from Hysterectomy

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## Abstract

This paper investigates why old and new medical technologies coexist. Health economics often focuses on tradeoffs that new medical technologies pose between cost and health benefits, but this paper shows that they can pose tradeoffs between multiple health dimensions. I develop a Roy model in which physicians and their patients choose a surgical procedure, considering how the procedure affects two important clinical outcomes, a patient's length of stay in the hospital and chance of readmission to the hospital. Laparoscopic surgery – a newer technology in which surgeons manipulate thin instruments through small incisions – results in shorter lengths of stay than abdominal, or open, surgery – an older, more invasive technology – yet not all surgical patients choose the laparoscopic procedure. The model shows that patients on the technology choice margin experience greater readmission risk under laparoscopic surgery than under abdominal surgery, although they experience shorter lengths of stay. I find evidence consistent with this prediction among Medicare-covered hysterectomy patients. I estimate the local average treatment effects and marginal treatment effects of laparoscopic surgery, relative to abdominal surgery, on patient outcomes using the difference between a patient's distance to her nearest laparoscopic surgery-performing hospital and the distance to her nearest hospital as an instrumental variable for choosing laparoscopic hysterectomy over abdominal hysterectomy. Compliers of the instrument are less likely to experience a long length of stay under laparoscopic hysterectomy than under abdominal hysterectomy, but they are more likely to have a hospital readmission. I also use the estimated local and marginal effects to calculate the revealed preference for shorter length of stay relative to lower readmission risk, which in the absence of hospital influence over the treatment choice could be considered a marginal rate of substitution.

JEL Classifications: I1, J0

Keywords: comparative advantage, health care productivity, medical technology, physician decision-making, surgery, women's health

## 1 Introduction

New technology can increase welfare by facilitating new products or services or improving the quality of existing ones. However, a new technology may present new tradeoffs relative to incumbent alternatives, in

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terms of service quality or costs. Much of the economics literature on medical technology diffusion considers the financial and strategic incentives of technology choice. There is a smaller literature that considers how technology’s impact on health affects choices over technologies, and it focuses on tradeoffs between health and costs. However, new medical technology can confer improvements on some dimensions of health while creating limitations or drawbacks on other dimensions. These tradeoffs may be important factors in the incomplete diffusion of new technologies throughout the industry.

My paper contributes to our understanding of the coexistence of laparoscopic surgery and abdominal surgery by showing that patients on the margin between these two alternative technologies face a tradeoff between improvement on two different dimensions of clinical quality. I study the choice between two alternative methods of total hysterectomy, the removal of the uterus and cervix: abdominal surgery, which entails making large incisions in the patient’s abdomen, and laparoscopic surgery, in which long, straight devices are inserted through small incisions in the abdomen to detach the specimens.<sup>1</sup> I construct a Roy model of the decision patients and their physicians jointly make over alternative surgical procedures. The model shows that among patients on the margin between laparoscopic and abdominal surgery, laparoscopic patients will experience shorter lengths of stay in the hospital than abdominal patients but will also experience greater readmission rates. This model is similar to the models in [Chandra and Staiger \(2007\)](#) and [\(2020\)](#), in which a patient and their physician choose between two courses of heart treatment – intensive care and medical management – based on which procedure yields higher utility for that given patient. The authors’ tests of their models’ hypotheses provide evidence that patients are triaged according to their “appropriateness” for intensive care. Chandra and Staiger do not try to pin down what drives a patient’s appropriateness. It may partly reflect relative differences in health production and costs, but it could also be driven by tradeoffs between different aspects of health production. In my model, patients and providers decide on a treatment based on how the available treatments affect the patient on two outcomes, rather than just one, the relative potential outcomes among marginal patients. I thereby generate empirical hypotheses consistent with two alternative treatments posing tradeoffs between two outcomes, for at least some patients.

The model also shows that estimates of the marginal treatment effects on these two health dimensions can be used to estimate a quantity reflective of the preferences in the health care system. If the treatment decision were entirely dependent on patient utility, then the quantity would equal the patient’s marginal rate of substitution between length of stay and readmission rate. If hospitals had preferences over treatment procedures and could influence treatment, then the quantity would reflect a combination of patient and

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<sup>1</sup>Abdominal and laparoscopic hysterectomy were the predominant methods of hysterectomy for many years. In the late 2000s, robotically assisted surgery became an increasingly common way to perform hysterectomy. I study the use and impacts of robotically assisted hysterectomy in other, ongoing work. In order to understand the determinants and the impacts of the diffusion of robotic surgery and the choice between the three alternatives of robotic, laparoscopic, and abdominal surgery, it is important and informative to first consider the prior, simpler choice between two surgical alternatives.

provider preferences.

I find empirical evidence consistent with the model’s predictions that marginal patients experience shorter lengths of stay under laparoscopic surgery than abdominal surgery but greater readmission rates. I estimate local average treatment effects of laparoscopic surgery (relative to abdominal surgery) on length of stay and readmission risk among hysterectomy patients observed in Medicare claims data using a patient’s distance to her nearest hospital that performs laparoscopic surgery relative to her nearest hospital as an instrumental variable for the decision to undergo laparoscopic, as opposed to abdominal, hysterectomy. This identification strategy, following [McClellan, McNeil and Newhouse \(1994\)](#), uses patients’ preference for health care providers who are closer to their residence.<sup>2</sup> I estimate that patients who comply with the relative distance instrument experience about a 55 percentage point lesser chance of a length of stay of 2 or more days under laparoscopic surgery than under abdominal surgery, but they also experience a 17 to 36 percentage point increase in the chance of a 90-day all-cause readmission.

I also find suggestive evidence consistent with the model’s predictions about how the treatment effects of laparoscopic surgery relative to abdominal surgery vary with respect to patients’ clinical “resistance” to or net “cost” of laparoscopic surgery. Some of the most important clinical factors that affect a patient’s propensity to undergo laparoscopic surgery rather than abdominal surgery, such as uterus weight and lifetime history of abdominal surgery and of delivery, are not detailed in the Medicare claims. I test the model’s predictions among patients with similar unobserved resistance to laparoscopic hysterectomy by estimating marginal treatment effects ([Björklund and Moffitt, 1987](#); [Heckman and Vytlačil, 1999, 2001](#); [Heckman, Urzua and Vytlačil, 2006](#)) of laparoscopic hysterectomy on length of stay and readmission rates. I again find that indifferent patients experience shorter lengths of stay and greater readmission rates under laparoscopic surgery than abdominal surgery. The model implies that the marginal treatment effects on readmission risk (positive, for at least the most resistant patients) and on length of stay (negative) should not both be decreasing with respect to patients’ unobserved resistance to laparoscopic surgery. More laparoscopic-resistant patients experiencing both lesser detrimental effects of laparoscopic surgery on readmission and greater beneficial effects on length of stay would contradict their being more resistant. I find suggestive evidence that the marginal treatment effects on length of stay are decreasing (i.e., increasingly negative) with respect to unobserved resistance and the effects on readmission risk are increasing, though the estimates are imprecise. These point estimates are consistent with one of the model’s core assumptions, that patients are heterogeneous in their potential clinical outcomes under the treatment alternatives. Furthermore, these point estimates tell a story similar to that of [Suri \(2011\)](#), who studies heterogeneity in farmers’ benefit

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<sup>2</sup>See [Burns and Wholey \(1992\)](#) and [Garnick et al. \(1990\)](#) for evidence and reviews of literature on distance’s role in patient choice of hospital, and see [Card, Fenizia and Silver \(2019\)](#) for a clarification of the relative distance identification strategy.

from and cost of using hybrid maize. She finds that the farmers who would experience the greatest benefit from the hybrid maize also face the highest costs and thus do not adopt it. I find patterns that suggest that patients with the greatest unobserved resistance to laparoscopic surgery would experience the greatest reductions in length of stay due to that procedure, but they also would experience the greatest increases in readmission risk. This paper demonstrates the use of methods from labor economics to better understand heterogeneity of treatment effects across patients with unobserved (to the economist) characteristics that affect their treatment decisions, or, “essential heterogeneity” (Heckman et al., 2006).<sup>3</sup>

The ratio of the estimates of the estimated local average treatment effects implies that the marginal rate of substitution of a percentage point of a long length of stay for a percentage point of readmission risk could be between  $-0.23$  and  $-0.66$ , depending on model specification. I also use the marginal treatment effect estimates at different levels of unobserved heterogeneity to calculate the marginal rates of substitution among patients with different propensities to undergo laparoscopic surgery, although these estimates are imprecise, reflecting the marginal treatment effect estimators’ imprecision. This ratio reflects patient preferences and, if hospitals can induce procedure choices by marginal physicians and patients, hospital objectives. In other words, this may reflect a combination of different actors’ preferences and objectives, rather than just a deep parameter of patient preferences. Much of the health economics literature on patient tradeoffs study patients’ consideration of price, distance, and provider quality in choosing among hospitals (e.g., Capps, Dranove and Satterthwaite, 2003), choosing whether to seek medical care (e.g., Manning et al., 1987; Finkelstein et al., 2012) or in choosing their use of pharmaceutical treatment (e.g., Duggan and Scott Morton, 2010). Ho and Pakes (2014) estimate elasticities reflecting a combination of patient and provider preferences and suggesting a willingness to trade off quality for price and distance for price, but not quality for distance (where “quality” is whatever hospital amenities explain revealed preference over hospitals beyond price and distance). An exception to the literature focusing on one quality dimension is Trajtenberg (1989), who studies how social welfare changes as a class of devices, namely, computed tomography (CT) scanners, evolve in multiple quality dimensions. Other exceptions study HIV patients choosing treatments over time and making tradeoffs between overall health improvement and side effects (Papageorge, 2016; Hamilton, Hincapié, Miller and Papageorge, 2021b; Hamilton, Hincapié, Kalish and Papageorge, 2021a). In the medical literature, Stewart, Lenert, Bhatnagar and Kaplan (2005) use vignettes to estimate patients’ relative utilities over complications and quality of life under different prostate cancer treatment regimes, and Barry, Fowler, Mulley, Henderson and Wennberg (1995) conduct an experiment to see if an educational program on prostate cancer treatment alternatives affects patient decision-making and satisfaction. This paper demonstrates that medical technologies may cause tradeoffs not just between health and costs but between one health dimension

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<sup>3</sup>See Basu, Heckman, Navarro-Lozano and Urzua (2007) for another application.

and another.<sup>4</sup>

My work shows that in medical “gray areas” (Chandra and Skinner, 2012) where there is a lack of straightforward professional guidance around treatment decisions, patients and providers weigh tradeoffs on multiple dimensions of clinical quality, so when marginal patients choose one alternative, they experience improved outcomes on one dimension, relative to the experience under the other alternative, but compromise quality on the other dimension. The choices over medical devices and procedures using different devices are important regions within the gray area. While there has been literature on regulatory approval of medical devices (e.g., Grennan and Town, 2020; Stern, 2017) and the purchase of medical devices (e.g., Grennan and Swanson, 2020; Craig, Grennan and Swanson, 2021), there has not been much recent literature on the use and health impacts of medical devices. An important exception is Cutler and Huckman (2003). They find that the introduction of a new invasive heart treatment – percutaneous transluminal coronary angioplasty (PTCA) – with lower unit costs than the incumbent intensive procedure – coronary artery bypass graft (CABG) – increased total costs among marginal patients who would have undergone less intensive medical management in the absence of the PTCA technology but decreased costs among patients who would have undergone CABG. They also find suggestive evidence that the introduction of PTCA led to improved quality of care for the patients who would not have undergone intensive care and, eventually, among the patients who would have undergone CABG. Additionally, Skinner and Staiger (2015) find that hospitals differ greatly in their speed of adopting effective and cost-effective heart treatment technologies – including cheap, effective drugs or angioplasty – and that this difference in adoption rates is large contributors to risk-adjusted survival rates across hospitals. While this small literature on procedure choice considers health to be one dimension of welfare, my work considers the heterogeneity of surgical technologies’ productivity on two dimensions across patient types.

My paper proceeds as follows. Section 2 describes the decision between laparoscopic and abdominal hysterectomy. In Section 3, I present the Roy model of patient and physician choices of surgical method and the predictions for marginal and average patients. I also demonstrate how the ratio of the effects on marginal patients identify the marginal rate of substitution of a longer length of stay for a lesser readmission rate. In Section 4, I describe data, including most importantly the Medicare claims. In Section 5, I present the instrumental variable I use to identify marginal treatment effects and the local average treatment effect, the relative distance instrument, and justify its validity for these purposes. The section also presents the

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<sup>4</sup>In this regard, my paper relates to literature on the diffusion of new technology outside of health care, in which it has been shown that the use of new technology in an industry or a locale requires an economical application of the technology or a general enough version of the technology to be developed for it to improve productivity in that industry or locale. For example, Goldfarb (2005) show that the use of electricity diffused into new industries once economical applications for electricity in those industries were invented, and Gross (2018) documents that farm tractors diffused across the United States depending on the predominant crops in a given area and whether the tractor designs marketed at the time were general enough for the technology to be productive on land with those crops.

two-stage least squares method for estimating the local average treatment effect and the local instrumental variable method and the separate method for estimating marginal treatment effects. [Section 6](#) presents tests of the side hypothesis using ordinary least squares regression results; tests of the main predictions, about marginal patients, using the two stage-least squared method, the local instrumental variable method, and the separate estimation method; and the estimates of the marginal rate of substitution between length of stay and readmission rate. [Section 7](#) describes the tests of the robustness of the main findings. [Section 8](#) discusses my theoretical and empirical findings and concludes.

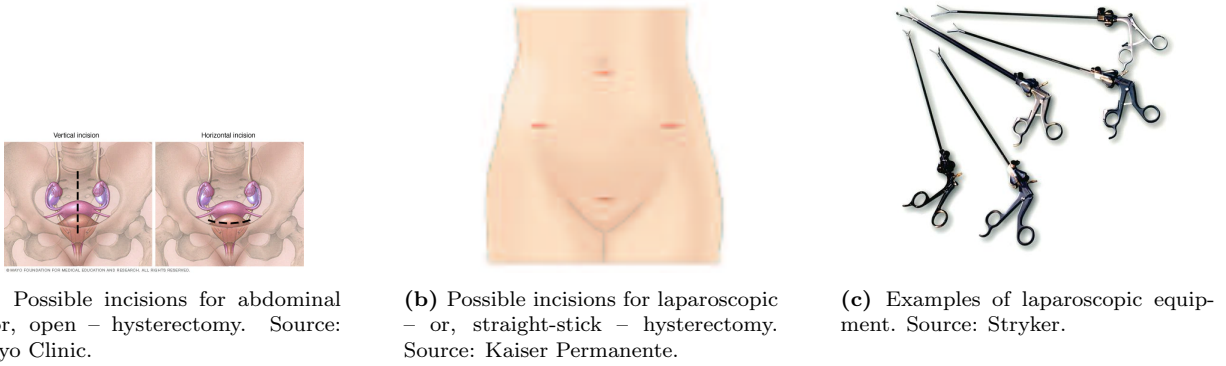
## 2 Total Hysterectomy

To evaluate a model of treatment decisions and the approach to estimating the marginal rate of substitution, I focus on total hysterectomy – the removal of the uterus and cervix – and the decision of whether to perform the surgery abdominally or laparoscopically. This is an ideal procedure for studying the choice of surgical mode. First, hysterectomy, the removal of the uterus, is a common and important procedure. 93,000 commercially insured hysterectomies ([Morgan et al., 2018](#)) and 39,000 Medicare-covered hysterectomies (author’s calculations) were carried out in the United States in 2012. It is used to treat several serious conditions, including uterine fibroids, endometriosis, pelvic organ prolapse, irregular bleeding, and uterine, ovarian, or cervical cancer.

Second, hysterectomy can be performed with different technologies. It can be performed abdominally ([Figure 1a](#)), in what is called an open procedure, or it can be performed in a minimally invasive way. Laparoscopic hysterectomy was introduced in 1988. It uses long probing equipment to translate movements of the surgeon’s hands into a smaller space in the patient’s body ([Figure 1b, 1c](#)). It thus is minimally invasive, and as such can result in less blood loss and less scarring than abdominal surgery. Some observational clinical studies suggest that laparoscopic hysterectomy patients may have shorter lengths of stay in the hospital on average than abdominal hysterectomy patients ([Aarts et al., 2015](#)). However, laparoscopic technology has some drawbacks. For example, it features diminished dexterity and visibility for the surgeons.

Third, different technologies for performing hysterectomy may have comparative advantages across different, heterogeneous patients. Some hysterectomy patients present with physical complexities that make laparoscopic technology less advantageous. For example, laparoscopic hysterectomy is more difficult and less feasible on patients with large uteruses, no history of vaginal births, histories of abdominal surgery, and histories of cancer. (See [American College of Obstetricians and Gynecologists \(2017\)](#) and [Walters and Ferrando \(2021\)](#) for evidence-based guidelines.)

Fourth, hysterectomy is an elective procedure. While it is used to treat many conditions that substan-



**Figure 1:** The long, slender nature of laparoscopic instruments allow hysterectomy to be performed with smaller incisions, but it also limit's the surgeon's dexterity.

tially diminish quality of life and, in some cases, threaten life, these conditions are rarely emergent. Thus, hysterectomy mode is likely to be chosen by weighing the comparative advantages of treatments in terms of the patient's clinical conditions and less likely than an emergent procedure to be chosen on some idiosyncratic provider-side basis like which doctor with which preferences or experiences was on-call on a particular night.

### 3 Theory of Surgical Treatment Choice

Here I present a [Roy \(1951\)](#)-style model of patients and physicians jointly making treatment decisions. In this setup, patients and physicians together decide which type of surgery for the patient to undergo, laparoscopic (subscript  $L$ ) or abdominal (subscript  $A$ ) hysterectomy. They make this decision in order to maximize the patient's utility<sup>5</sup>, which is primarily a weighted function of two adverse clinical outcomes, length of stay,  $S$  and readmission rate,  $R$ , and the distance a patient would need to travel to undergo the surgical procedure,  $T_L$  or  $T_A$ . This is in keeping with the models of [Chandra and Staiger \(2007, 2020\)](#), who consider treatment decisions made to maximize patient survival. However, in my paper, I consider treatments that affect two clinical outcomes and that might have comparative advantages for different outcomes. If treatments have different comparative advantages over the two outcomes, then the choice will be affected by patients' (and physicians') relative marginal disutilities for the two adverse clinical outcomes.

Length of stay and readmission rates are very plausible prominent features in the patient–physician indifference curve. These clinical care outcomes are commonly studied in the medical and health services research literature comparing efficacy of treatments and practice patterns, and they are subject to regulatory scrutiny under health care finance policy. Length of stay is likely also correlated with other outcomes of interest like blood loss and immediate complications, and readmission rate is inherently related to onset of

<sup>5</sup>One could consider the physician in [Ellis and McGuire \(1986\)](#)'s model, with the parameter governing the weight the physician places on patient health relative to hospital profits set so that the physician only cares about patient health.

complications after the first inpatient stay.

The model also incorporates the patient’s disutility of travel time to the facility for the procedure. A patient’s distance to different hospitals is an important determinant of her choice of hospital. (Gaynor and Vogt (2000) review some of the prior evidence.) Different hospitals have equipment and staffs with different capabilities, so some hospitals perform laparoscopic surgery while other perform only abdominal surgery. Thus, distance of a patient to hospitals with laparoscopic technology relative to hospitals performing just open surgery affects her utility for laparoscopic surgery. This model feature will be used in the empirical strategy (section 5) for identifying effects among marginal patients.

### 3.1 Model

Let there be patients whose heterogeneity in clinical conditions can be characterized as a random variable  $\theta$  that realizes values from zero to one. This might describe the physical complexity of a patient’s case, with one representing more complex cases. Let the production of patient outcomes length of stay,  $S$ , and readmission rate,  $R$ , under each treatment method  $j \in L, A$ , for a given value of complexity  $\theta$  be:

$$S_j(\theta, X, W_{S,j}) = \alpha_j + \beta_j\theta + \kappa_{S,j}X + W_{S,j} \quad (1)$$

$$R_j(\theta, X, W_{R,j}) = \gamma_j + \delta_j\theta + \kappa_{R,j}X + W_{R,j} \quad (2)$$

where all parameters are positive,  $X$  is a random vector of patient characteristics affecting the clinical outcomes, and  $W_{S,j}$  and  $W_{R,j}$  are random variables of mean zero representing idiosyncratic factors determining a patient’s adverse outcomes. Condition on  $X$  and the idiosyncratic terms.

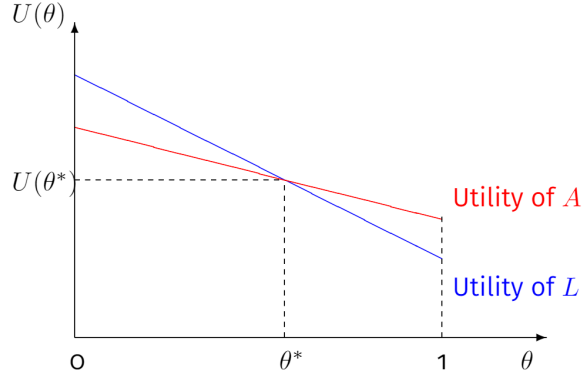
The patient–physician pair’s joint indirect utility function depends on two adverse clinical outcomes –  $S$  and  $R$  – and the patient’s distance or travel time to the hospital where procedure  $j$  is performed,  $T_j$ :

$$U_j(\theta, T_j) = u^B - \omega_S S_j(\theta) - \omega_R R_j(\theta) - \omega_T T_j \quad (3)$$

where  $u^B$  is “bliss utility,” a maximum level of utility that could be achieved from the surgery but that is generally unattainable.

Either one procedure type is performed for all patient types (i.e., all values of  $\theta$ ) or one procedure is performed for only some values of  $\theta$ . Let us assume that no procedure is performed for all patient types. This is consistent with observations that both laparoscopic and open hysterectomies are performed within surgical services markets. For a given value of  $Z \equiv T_L - T_A$ , the laparoscopic procedure yields higher utility





**Figure 2:** Utility of minimally invasive surgery and abdominal, or open, surgery as functions of patient type  $\theta$ . Need to change L to M.

on one range of values of  $\theta$ , and on the complementary interval, abdominal surgery yields higher utility. In this model and those of [Chandra and Staiger \(2007, 2020\)](#), the partition of the type interval into two intervals on which each procedure dominates follows from the linear production functions, but a “single crossing” of the utility functions with respect to  $\theta$  does not require such functional form assumptions. Indeed, [Roy \(1951\)](#) describes what is essentially a single-crossing without assuming functional forms of agents’ utility, merely by assuming that the variance of outcomes of agents who made one choice is different from the variance of outcomes among agents who made the other choice.<sup>6</sup>

If  $\theta$  represents case complexity, I argue it is more plausible that low- $\theta$  patients experience higher utility under laparoscopic surgery than under abdominal surgery and that abdominal surgery has a comparative advantage among patients with high  $\theta$ , conditional on  $Z$  ([Figure 2](#)). Laparoscopic equipment has less dexterity and more limited visibility than abdominal surgery. Thus it is more difficult for surgeons to suture, make incisions, or see the anatomy of patients with trickier physical presentations and is incapable of performing some procedures like biopsies that accompany complex cases. For example, hysterectomy patients with large uteruses, patients who did not deliver any births vaginally, patients with histories of abdominal surgery, patients with history of cancer, and patients in other situations in which a specimen to be removed is near another internal organ like the colon present the surgeon with anatomical complexities for which surgery might benefit from more dexterity.

Additionally, assume that for all levels of  $\theta$ ,

<sup>6</sup>The assumptions of the production functions here – namely, that outcomes under the two alternatives are linear with the same-signed slopes but with the one production function’s slope steeper than the other – lead to similar predictions about outcomes for marginal agents as [Roy \(1951\)](#)’s assumptions that the log Normal-distributed random variables representing productivity in his two labor sectors are positively correlated with the fishing sector’s productivity over potential workers having greater variance than the other. If the patient’s utility were over just one outcome, the change in utility of the marginal patient when the nearest laparoscopic hospital is moved closer to her has the same sign as the change in the earnings of Roy’s marginal worker when the (exogenous) price of fish increases.

$$S_L(\theta) < S_A(\theta) \quad (4)$$

which is consistent with the observation that laparoscopic equipment's smaller incisions are less invasive than open surgery and thus should result in less blood loss, less scarring, and shorter recovery times.

### 3.2 Choices by Different Patient Types

This section shows how the utility functions under laparoscopic surgery and under abdominal surgery and the adverse outcome production functions affect choices among patients with, alternatively, low and high  $\theta$  types. Derivations of the findings are in [Appendix A](#).

Consider the indifference curve of patient type  $\theta = 0$  for fixed  $Z$  ([Figure 3a](#)) in terms of  $S$  and  $R$ , conditional on  $X$ , and the random shocks  $W_{S,A}$ ,  $W_{S,L}$ ,  $W_{R,A}$  and  $W_{R,L}$ . Note that the slope of the indifference curve is  $m = -\frac{\omega_S}{\omega_R}$ . Bliss utility,  $u_B$ , travel time,  $T_j$ , and preference weight on travel time,  $\omega_T$ , are encoded in the indifference curve's  $R$ -intercept:

$$R(\theta) = \frac{u_B - \omega_T T_j}{\omega_R} - \frac{\omega_S}{\omega_R} S(\theta) \quad (5)$$

Each point represents a bundle of adverse clinical outcomes, and points  $L^0$  and  $A^0$  represent the bundles that type  $\theta = 0$  can achieve under the two production technologies available  $L$  and  $A$ , respectively. Highest utility is achieved at the origin, and utility declines as  $S$  or  $R$  increases, conditional on  $(T_L, T_A)$ . From the assumption that low complexity cases choose  $L$ , [Appendix A](#) shows that the production possibilities must lie on a line that is shallower than the indifference curve, and so type  $\theta = 0$  patients experience shorter lengths of stay but greater readmission risk under laparoscopic surgery than under abdominal surgery (depicted in [Figure 3a](#)). High-complexity, type  $\theta = 1$  patients choose abdominal surgery, under which they experience a lesser readmission risk but longer length of stay ([Figure 3b](#)). [Appendix A.3](#) shows that, for a given value of the difference in distances,  $T_L - T_A$ , there exists a  $\theta^*$  such that patients are indifferent between laparoscopic and abdominal surgery.

### 3.3 Predictions about Outcomes among Patients on the Treatment Margin

There is one  $\theta$  for a given  $Z = T_L - T_A$  such that the patient is indifferent between procedures. For a given value of  $Z$ , call this  $\theta^{LA}(Z) = \theta^*$  to simplify notation.

For a patient indifferent between laparoscopic and abdominal surgery, it is true that

$$\omega_S \cdot (S_A(\theta^*) - S_L(\theta^*)) - \omega_T \cdot Z = \omega_R \cdot (R_L(\theta^*) - R_A(\theta^*)) \quad (6)$$

where  $\theta^{LA}(Z) \equiv \theta^*$  is the value of  $\theta$  for which a given value of  $Z = T_L - T_A \geq 0$  makes the patient indifferent.<sup>7</sup>

Appendices A.2 and A.3 show that it follows from the comparative advantage assumption (that low- $\theta$  types choose laparoscopic surgery and high- $\theta$  types choose abdominal surgery) that the complexity type of the patient who is indifferent,  $\theta^*$ , decreases when  $Z$  increases. Let's refer to the component of utility that is affected by complexity type  $\theta$  but excludes the disutility of travel time,  $u_B - \omega_S S(\theta) - \omega_R R(\theta)$ , as clinical utility. Patients who are indifferent between the treatment methods when  $Z = 0$  have less relative clinical utility from laparoscopic surgery than patients who are indifferent for a large  $Z$  – i.e., for patients who are indifferent when the laparoscopic hospital is much farther from their residence than the hospital without laparoscopic surgery.

Now let's analyze the difference in potential readmission rates for patients who are indifferent, i.e., for whom Equation (6) holds. Recall the earlier assumption that  $S_L(\theta) < S_A(\theta)$  for all values of  $\theta$ , because laparoscopic surgery is always less invasive than abdominal surgery. The patient who is indifferent at  $Z = 0$  must have a greater readmission rate under laparoscopic surgery than under abdominal surgery, i.e.:

$$R_L(\theta^{LA}(Z = 0)) - R_A(\theta^{LA}(Z = 0)) < 0 \quad (7)$$

The changes in the differences in potential outcomes among indifferent patients when  $Z$  increases, or equivalently, when considering patients with greater relative clinical utility from laparoscopic surgery, are:

$$\frac{d[S_L(\theta^*) - S_A(\theta^*)]}{dZ} = \omega_T \cdot \left( \frac{\beta_L - \beta_A}{\omega_S(\beta_A - \beta_L) - \omega_R(\delta_L - \delta_A)} \right) \quad (8)$$

$$\frac{d[R_L(\theta^*) - R_A(\theta^*)]}{dZ} = \omega_T \cdot \left( \frac{\delta_L - \delta_A}{\omega_S(\beta_A - \beta_L) - \omega_R(\delta_L - \delta_A)} \right) \quad (9)$$

It follows from the comparative advantage assumption that the two derivatives cannot both be positive (see Appendix A.4).

In summary, the model says that among marginal patients, the relative readmission rate under laparoscopic surgery,  $R_L(\theta^*) - R_A(\theta^*)$ , will be positive for marginal patients with the least relative clinical utility

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<sup>7</sup>Recall that  $Z$ , the difference between a patient's distance to her nearest laparoscopic-performing and hysterectomy-performing hospital,  $T_L$ , and the distance to her nearest hysterectomy-performing hospital,  $T_A$ , is weakly positive. All hysterectomy-performing hospitals perform abdominal surgery, but not all hysterectomy-performing hospitals perform laparoscopic surgery.

for the laparoscopic method, if not for marginal patients of all types. The differences in potential lengths of stay,  $S_L(\theta^*) - S_A(\theta^*)$ , (which is taken to always be negative) and the differences in potential readmission rates will each be either increasing or decreasing with respect to patient’s relative clinical utility of laparoscopic surgery, but they cannot both be increasing.

### 3.3.1 Estimands: Empirical Implications of the Model

What empirical questions does this theory lead to? This subsection shows that the predictions about outcomes among indifferent patients with a given level of unobserved resistance to laparoscopic surgery (i.e., a given level of relative health “costs” to laparoscopic surgery unobserved by the analyst) leads to predictions about *marginal treatment effects* and, in turn, *local average treatment effects*. Consider the relative utility under laparoscopic surgery,  $L$ , versus under abdominal surgery,  $A$ , rearranging terms:

$$\begin{aligned}
& U_L(\theta, T_L, X, W_{S,L}, W_{R,L}) - U_A(\theta, T_A, X, W_{S,A}, W_{R,A}) \\
&= \underbrace{\omega_S(\alpha_L - \alpha_A + W_{S,L} - W_{S,A}) + \omega_R(\gamma_L - \gamma_A + W_{R,L} - W_{R,A}) + [\omega_S(\beta_A - \beta_L) + \omega_R(\delta_L - \delta_A)]\theta}_{\equiv V, \text{ unobserved}} \\
&+ \underbrace{\omega_T(T_L - T_A) + [\omega_S(\kappa_{S,L} - \kappa_{S,A}) + \omega_R(\kappa_{R,L} - \kappa_{R,A})]X}_{\equiv \mu(Z, X), \text{ a function of observables}}
\end{aligned} \tag{10}$$

The indirect utility determining whether a patient with covariates  $X$  and excluded instrument value  $Z = T_L - T_A$  undergoes laparoscopic surgery can be represented as a sum of a function of observed case characteristics,  $\mu(Z, X)$ , and an additively separate unobserved term represented by random variable  $V$ . The indicator function for whether patients with  $(X, Z, V)$  undergo laparoscopic surgery (as opposed to abdominal surgery) is

$$D_L(X, Z, V) = \mathbb{1} [\mu(Z, X) - V \geq 0] \tag{11}$$

where  $V$  has some distribution and arbitrarily depends on  $\theta$  and the idiosyncratic outcome shocks,  $W_{S,L}$ ,  $W_{R,L}$ ,  $W_{S,A}$ , and  $W_{R,A}$ . Equivalently, it depends on all factors affecting outcomes that aren’t included in  $X$ . In my empirical setting,  $X$  includes a number of comorbidities and gynecological conditions recorded in Medicare claims (as I will detail in the data section, [Section 4](#)). Therefore,  $V$  represents determinants of the outcomes and, in turn, of the choices that I do not observe in the Medicare claims: uterus weight, history of vaginal births, history of abdominal surgery, and other anatomical conditions that I do not observe but that

the physician and patient do observe and that affect the efficacy of laparoscopic surgery.  $V$  can be thought of as the unobserved (to the analyst) net “health cost” or “resistance” to choosing laparoscopic surgery. Following the literature on selection on unobservable heterogeneity (for example, [Carneiro, Heckman and Vytlačil, 2011](#)), let  $U_D$  denote the cumulative distribution function of  $V$ ,  $F_V(V)$ , so it represents a case’s percentile of unobserved “resistance” to the laparoscopic choice. Now we may consider a causal parameter of interest called the *marginal treatment effect* on outcome  $Y$  – first proposed by [Björklund and Moffitt \(1987\)](#) and further developed by [Heckman and Vytlačil \(1999, 2000, 2005, 2007\)](#). The marginal treatment effect of treatment  $L$ , relative to treatment  $A$ , on outcome  $Y$  is defined as

$$MTE_Y(x, u_D) \equiv \mathbb{E}[Y_L - Y_A | X = x, U_D = u_D] \quad (12)$$

and it is evaluated at a vector of particular covariate values,  $x$ , and at a particular percentile of unobserved “cost” of or resistance to treatment,  $u_D$ , or is commonly called, “resistance” to the laparoscopic treatment.

Different instrument values identify marginal treatment effects among patients with different levels of  $\theta$ . Patients with lower  $\theta$ , a key aspect of the theory which represents patient complexity that makes a patient more resistant to laparoscopic surgery, have lesser  $V$  and thus a lesser  $U_D$ . Consider the propensity score for choosing laparoscopic surgery as a function of covariates and an excluded instrument,  $P(z, x) \equiv \Pr(D_L = 1 | Z = z, X = x)$ <sup>8</sup>. Note that  $U_D$  and  $P(X, Z)$  are monotonic transformations of  $V$  and  $\mu(Z, X)$ , respectively. A patient who is at a lower percentile of unobserved resistance to the laparoscopic procedure,  $U_D$ , requires a lower percentile of observed net benefit,  $P(Z, X)$  – induced by a greater relative distance to the laparoscopic surgery-performing hospital,  $Z$  – in order to be indifferent between laparoscopic surgery and abdominal surgery. Therefore, patients with lower  $\theta$  have lesser  $V$  and lesser  $U_D$ , and thus their marginal treatment effects are identified by lesser values of  $P$  induced by greater relative distances,  $Z$ .

This also demonstrates why the marginal treatment effect is sometimes described as the difference in potential outcomes among patients who have values of  $(Z, X)$  such that their unobserved resistance to laparoscopic treatment,  $u_D$ , is equal to their observed net benefit of laparoscopic surgery,  $P(Z = z, X = x) = p$ , so  $MTE_Y(x, u_D) = MTE_Y(x, p)$ .

With causal quantities defined and identification explained, let us now turn to the empirical implications of the model. Let the notation implicitly condition on  $X$ . The assumption made that  $S_L(\theta) < S_A(\theta)$  for all  $\theta$  implies that empirically the marginal treatment effect on length of stay is

$$MTE_S(u_D) < 0 \quad (13)$$

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<sup>8</sup>This is sometimes characterized as the patient’s mean scale utility value.

for any given  $u_D$ . Equation (7) predicts that the marginal treatment effect on readmission risk among patients with the greatest resistance to laparoscopic surgery is positive, i.e.

$$MTE_R(P(Z = 0)) > 0 \quad (14)$$

Recall that patients at the highest percentile of resistance (i.e., greatest  $U_D$ , 1 by definition) are identified and made indifferent between surgery alternatives by the lowest instrument value,  $Z = 0$ . Since marginal treatment effects on readmissions is positive for the highest resistance patients, if  $MTE_R(u_D)$  is continuous, then

$$MTE_R(u_D) > 0 \quad (15)$$

for an interval  $u_D \in [u_D^0, P(Z = 0)]$  if  $\frac{\partial MTE_R(u_D)}{\partial u_D} > 0$ , where  $u_D^0$  is some value less than one, or for all  $u_D$  otherwise. In other words, the marginal treatment effects on readmissions should be positive for the patients with the greatest resistance to treatment, if not all patients.

The analysis resulting in Equation (8) and Equation (9) also predicts that

$$\frac{\partial MTE_R(u_D)}{\partial u_D} \geq 0 \quad (16)$$

$$\frac{\partial MTE_S(u_D)}{\partial u_D} \geq 0 \quad (17)$$

as long as they are not both positive, for any  $u_D$ . Both derivatives being positive would contradict the meaning of  $U_D$  as the percentile of unobserved resistance to laparoscopic surgery. It would mean that patients with greater unobserved resistance to laparoscopic surgery,  $U_D$ , experienced both greater detriment from laparoscopic surgery (more positive  $MTE_R$ ) and lesser benefit from laparoscopic surgery (less negative  $MTE_S$ ).

The marginal treatment effects are related to the local average treatment effect on outcome  $Y$ ,

$$LATE_Y = \frac{\text{Cov}(Y, Z)}{\text{Cov}(Z, D_L)}$$

for continuous  $Z$ .<sup>9</sup> As discussed in the context of marginal treatment effects, a particular value of  $Z$  induces

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<sup>9</sup>It is interpreted as the difference in potential outcomes among the compliers of the instrument, that is, among patients who

a propensity score  $p$  and identifies marginal treatment effects among patients with a  $u_D$  equal to  $p$ . Heckman and Vytlačil (1999, 2005) and Heckman, Urzua and Vytlačil (2006) show that the local average treatment effect on outcome  $Y$  for an instrument whose values induce a range of propensity scores from  $p_0$  to  $p_1$ , is a weighted combination of marginal treatment effects:

$$LATE_Y(p_0, p_1) = \int_{p_0}^{p_1} MTE_Y(p) \varphi_{IV}^Z(u_{D_L}) dp \quad (18)$$

where  $\varphi_{IV}^Z(u_D)$  are the weights for each level of  $u_D$ .<sup>10</sup>

This leads to the predictions

$$LATE_R > 0 \qquad \qquad \qquad LATE_S < 0 \quad (19)$$

To test the theory's predictions about marginal patients in my empirical setting, I will first estimate the local average treatment effect as an approximation of the marginal treatment effects, and then I will estimate the marginal treatment effects for different levels of  $U_D$  under several model specifications.

### 3.4 Revelation of Preferences and Objectives

Assuming that the choice of hysterectomy mode is made jointly by a patient and physician who are trying to maximize patient utility over the two clinical outcomes and travel time to surgery, the model shows how to identify patients' and physicians' joint marginal rate of substitution. Since the slope of the indifference curve for a given tuple  $(\theta, Z)$  is equal to the marginal rate of substitution,  $MRS_{S,R} = (\partial U / \partial S) / (\partial U / \partial R) = -\frac{\omega_S}{\omega_R}$ , the ratio of the marginal treatment effects of the two outcomes equals the marginal rate of substitution:

$$MRS_{S,R}(\theta) = m = \frac{R_A(\theta) - R_L(\theta)}{S_A(\theta) - S_L(\theta)} \quad (20)$$

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would choose  $D_L = 1$  for some values of  $Z$  and would choose  $D_L = 0$  for other values. The denominator is the first stage, and the numerator is the reduced form or the intent-to-treat effect.

<sup>10</sup>The weights relating the MTEs to the LATE are:

$$\varphi_{IV}^Z(u_D) = \frac{\mathbb{E}[Z - \mathbb{E}[Z] \mid P(Z) > u_D] \Pr(P(Z) > u_D)}{\text{Cov}(Z, D)}$$

Certain observations are weighted more heavily if their treatment covaries with particular ranges of the instrument more. The weights integrate to one, can be negative if the instrument does not satisfy monotonicity, and can be consistently estimated from the sample.

for each  $\theta$ . Thus, in the population, the marginal rate of substitution for patients with unobserved resistance to laparoscopic surgery  $u_D$  is identified by

$$MRS_{S,R}(u_D) = \frac{MTE_R(u_D)}{MTE_S(u_D)} \quad (21)$$

the ratio of the marginal treatment effects on readmissions and on length of stay. Because the local average treatment effect is a weighted combination of the marginal treatment effects identified by the instrument, I also approximate the marginal rate of substitution across case complexity types using the local average treatment effect. If the marginal rate of substitution is the same across patient types, which would happen if indifference curves were linear, then

$$MRS_{S,R} = \frac{LATE_R}{LATE_S} \quad (22)$$

the ratio of local average treatment effects is the marginal rate of substitution for any patient type. Otherwise, it is a weighted combination of marginal rates of substitution across patients types.

I should make an important caveat here. The finding that the ratio of the marginal effects identifies the marginal rate of substitution for patients depends on providers fully and accurately incorporating patient preferences into their own utility function. [Sepucha and Mulley \(2009\)](#) review some potential reasons why physicians might not understand or implement a given patient’s preferences. Additionally, this identification requires there to be no other provider-side factors influencing the choice of hysterectomy mode. For example, hospitals’ profit functions, or in the case of not-for-profit hospitals, their utility functions ([Pauly and Redisch, 1973](#)), could incorporate patient length of stay or readmission risk. Patient length of stay could affect hospital profit margins on episode-based or capitated payment, and readmission risk could affect patient’s quality measures which could in turn affect hospitals’ bargaining leverage with insurers. (However, at the time of my observations, Medicare did not have financial penalties for readmissions.) If hospitals are able to influence surgical mode through allocation of operating room equipment, staff, and time or through other tacit ways, the “marginal rate of substitution” identified by the ratio in [Equation \(20\)](#) does not merely identify the patient marginal rate of substitution – i.e. some function of patients’ relative elasticities of demand with respect to clinical outcomes – but rather the ratio would reflect preferences and incentives throughout the health care system.<sup>11</sup>

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<sup>11</sup>Differences in physician reimbursement or physician ergonomics between the modes, for example, could affect the decision, and these factors would be incorporated in the intercepts of the linear indifference curves considered here, rather than the slope,



### 3.5 Predictions about Difference in Mean Outcomes between Treatment Groups

This section shows that the model makes predictions about differences in mean outcomes between patients making different surgical mode choices. These constitute an additional side hypothesis whose confirmation would further support the model. Taken together with the predictions for marginal patients, it also makes an interesting point that behavior under this model is consistent with a local average treatment effect on readmission being a different sign than the estimate of the difference in means. In other words, the estimated sign of the effect of laparoscopic surgery on readmissions could be different in a two-staged least squares regression than in an ordinary least squares regression. Conventionally, a difference in signs estimated from these two types of regressions is considered a cause for concern for the estimation's validity, but under this model it is plausibly expected with a valid instrument.

The difference in means of length of stay between laparoscopic patients and abdominal patients is:

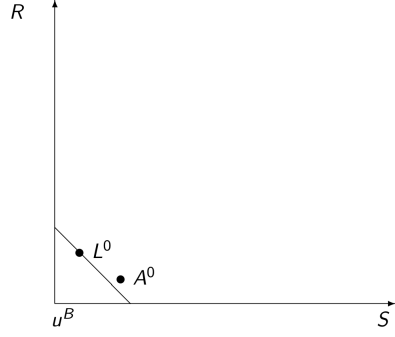
$$\bar{S}_L - \bar{S}_A < 0 \quad (23)$$

So the ordinary least squares estimate of the effect of laparoscopic surgery, relative to abdominal surgery, on length of stay, among patients who undergo either laparoscopic or abdominal surgery will be positive.

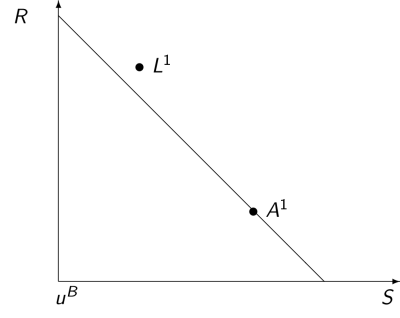
The sign of the difference between the mean readmission rate among laparoscopic patients and the mean readmission rate among abdominal patients is ambiguous under the presented assumptions. It is dependent on an interaction of the differences between technologies in readmission rates among patients without complications, in the degrees to which readmission rates increase with respect to  $\theta$ , and the shares of patients of each technology choice who are of different values of  $\theta$ . [Appendix A.5](#) goes into more detail and analyzes the possible cases. The upshot is, the sign of  $\bar{R}_L - \bar{R}_A$  is ambiguous. Whether the difference in means is positive or negative is not dependent on the sign of the treatment effect among the marginal patients, whose treatment effect would be approximated by the local average treatment effect. In other words, in this selection setting, theory allows for the sign of the local average treatment effect to be different from the sign of the ordinary least squares estimate of the treatment effect. This departs from the conventional notion that a contradiction between the sign of the estimated local average treatment effect and the sign of the ordinary least squares estimate of the average treatment effect is a cause for concern about the instrumental variable regression's validity. Theory predicts that the signs will be different under certain reasonable parameter assumptions and distributional assumptions.

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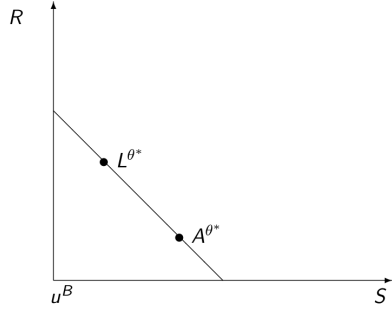
unless these technology-specific factors in the physicians' utility were correlated with length of stay or readmission rate. (See [Newhouse \(1996\)](#) for a literature review on provider response to reimbursement contract design, and see [McDonald et al. \(2014\)](#) for a small survey of gynecologic oncologists on ergonomics of different surgery types.)



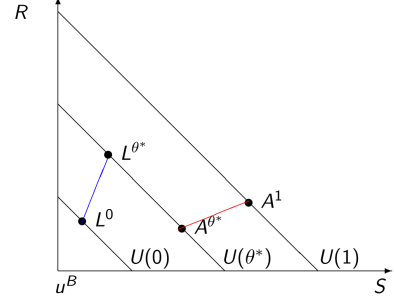
(a) Patients of complexity type  $\theta = 0$



(b) Patients of complexity type  $\theta = 1$



(c) Patients of complexity type  $\theta = \theta^*$  such that the patient is indifferent between options.



(d) Indifference curves and production possibilities sets for patient types 0,  $\theta^*$ , and 1

**Figure 3:** Indifference curves and production sets for patients of three different complexity types,  $\theta = 0$ ,  $\theta = \theta^*$  for the  $\theta^* \in (0, 1)$  such that patients are indifferent between laparoscopic and abdominal surgery, and  $\theta = 1$ . The production set for patient type  $\theta$  is composed of two bundles of patient outcomes labeled  $L^\theta$  if laparoscopic surgery is chosen and  $A^\theta$  if abdominal surgery is chosen. Bundles are composed of a readmission rate  $R$  and a length of stay in the hospital,  $S$ . Utility is highest at the origin point,  $u^B$ , and decreases outward, i.e., up and to the right. Bundles chosen by laparoscopic patients will fall in the area around the blue line connecting  $L^0$  and  $L^{\theta^*}$  in Panel D, and bundles chosen by abdominal patients will fall around the red line connecting  $A^{\theta^*}$  and  $A^1$ .

### 3.5.1 Estimands

Finally, to test the model’s side prediction about the difference in the average length of stay among the laparoscopic patients and among the abdominal patients in [Equation \(23\)](#), I estimate the difference in expected lengths of stay among patients with the same covariates, and I predict it to be

$$\mathbb{E}[S|D_L = 1, X] - \mathbb{E}[S|D_L = 0, X] < 0 \quad (24)$$

The prediction for the difference in the expected readmission rates

$$\mathbb{E}[R|D_L = 1, X] - \mathbb{E}[R|D_L = 0, X] \quad (25)$$

is ambiguous.

## 4 Data Description

Testing this paper’s theory requires estimating the impacts of the choice of surgical technology on patient outcomes. For this, I require data on patients who underwent total hysterectomy performed by different physicians, in different hospitals, in different procedure markets, and I require detailed information about patient characteristics, the physicians and hospitals that provided the surgery, and patient diagnostic information recorded during the stay of the surgery and in subsequent encounters with health care providers.

Medicare claims data is well suited for this investigation. I analyze all Medicare inpatient claims throughout the United States from 2007 to 2008. This is to say that I observe virtually all inpatient stays among Americans age 65 and older, of all different demographics and clinical characteristics, in all various geographical settings and hospital market structures, treated by physicians with all different experiences and training. I use data from 2007 to 2008 because at this time, almost all Medicare-covered total hysterectomies were performed either laparoscopically or abdominally.

There were very few Medicare outpatient claims for hysterectomy in this period (141 hysterectomies in 2007, including total, subtotal, and radical hysterectomies). The few that I observe may be part of a different data generating process than the inpatient hysterectomies and are a very small segment of the hysterectomies in the population, so I do not include them in my analysis here.

I observe 60,889 claims for total hysterectomies from 2007 to 2008, six percent of which are for laparoscopic hysterectomies. Each claim includes a unique identifier for patients, allowing me to see information from

multiple health care encounters for a given patient, such as whether a patient was readmitted to a hospital after a hysterectomy. The patient identifier also allows linking a claim to Medicare’ beneficiary summary file, which contains demographic information and the Zip code of the patient’s resident. It also includes ICD-9 procedure codes and diagnosis codes, providing detailed, standardized information about the clinical characteristics of the patients as well as the care provided. ICD-9 procedure codes include detailed description of the type of surgery performed, including whether a hysterectomy was open/abdominal, laparoscopic, or robotically-assisted.<sup>12</sup> The claim also indicates the dates of admission and discharge, allowing for calculation of the patient’s length of stay in the hospital. Finally, the claims also detail the Zip codes of the hospitals and of the patients, facilitating my identification strategy that relies on comparing a patient’s distance to her nearest hospital with minimally invasive surgery to her nearest hospital that does not perform minimally invasive surgery.<sup>13</sup>

From the claims, I derive my outcomes of interest. For each total hysterectomy, I build an indicator variable for whether the patient’s length of stay in the hospital was two or more days and an indicator variable whether the patient had an inpatient claim in the 90 days since the hysterectomy. I choose use a dichotomous measure of the length of stay because the distribution of length of stay has much of its probability mass around one or two days and a long right tail (see Appendix Figure 10). Thus, much of the possible potential lengths of stay are around two days. Additionally, some unusual cases with long length of stay could have outsized influence on the treatment-specific means, so making inferences about mean length of stay may not be as informative as making inference about the frequency with which length of stay is above a common realization.

In order to condition my estimates of course of treatment on outcomes on possibly confounding factors, I augment this data with information from a few sources. To control for characteristics of the patient’s neighborhood which may be correlated with their own socioeconomic characteristics, I collect Zip Code Tabulation Area-level data on race, income, rates of participation in public assistance and public insurance programs, and household income from the U.S. Census Bureau’s American Community Survey’s 5-Year Estimates from 2008 – 2012. I also use hospital quality measures from Medicare’s Hospital Compare program. Finally, I observe some hospital characteristics through Medicare’s Provider of Service (POS) file.<sup>14</sup> The

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<sup>12</sup>The ICD-9 procedure code for robotically-assisted surgery was not introduced until the fourth quarter of 2008; prior to that point, robotically-assisted procedures were coded as laparoscopic procedures. However, according to these claims, only 5.2 % of hysterectomy claims in that quarter were performed in a robotically-assisted manner, 5.7% in the first quarter of 2009, 7.8% in the second quarter, and 10.5% in the first quarter of 2010 (Figure 9 in the appendix). Even though I do not directly observe whether a given hysterectomy in 2007 or the beginning of 2008 was performed robotically, I infer from this trend that it is probably true that very few of the hysterectomies coded as laparoscopic from 2007 to 2008 were performed robotically.

<sup>13</sup>I calculate the distances between the centroids of the Census Bureau’s Zip code tabulation areas, the latitude and longitudes of which are calculated and made publicly available by UDS Mapper (Bureau of Primary Health Care at the U.S. Health Resources and Services Administration; John Snow, Inc.; and the American Academy of Family Physicians; available at <https://udsmapper.org>), using the distHaversine function for R.

<sup>14</sup>I use a version of the file cleaned and made publicly available by Adam Sacarny, <http://sacarny.com/data/>.

specific covariates I control for are detailed in the section on empirical strategy.

I have several groupings of covariates, which I add sequentially to the regression specification to see how robust the estimate is to potential confounding factors. Demographic controls include indicators for whether the patient is Black, a race other than white or Black, under 65 years of age, or over 74 years of age. Clinical controls include the Charlson comorbidity index as well as indicators for whether the patient had diabetes, had a malignant neoplasm, had a non-malignant neoplasm, had a body mass index of 30 or over (considered obese), had a history of cancer indicated on the hysterectomy claim, had uterine fibroids, had endometriosis, had pelvic organ prolapse, had female genital bleeding, had post-menopausal bleeding, had an ovarian cyst, had female genital pain, or had peripheral adhesions. Variables describing the Zip code of the patient's residence include the white percent of residents, the college-educated percent of residents, the percent of residents with public assistance (including cash or nutritional assistance), the median household income, and the percent of residents on Medicaid. The hospital quality variables include how many hysterectomies the hospital performed that year, a quality measure on the appropriate use of antibiotics, a quality measure on the prevention of blood clots in heart patients, and the overall Consumer Assessment of Healthcare Providers & Systems (CAHPS) score.

[Table 1](#) show how patient diagnoses, comorbidities, and demographics vary by hysterectomy mode.

**Table 1:** Means and Standard Deviations of Case Characteristics, by Total Hysterectomy Approach

	Laparoscopic		Abdominal	
	Mean	Standard Deviation	Mean	Standard Deviation
Percent with Any Readmission	0.122	0.327	0.165	0.371
Percent with Length of Stay $\geq 2$ Days	0.522	0.500	0.982	0.135
White	0.867	0.339	0.816	0.387
Black	0.0927	0.290	0.137	0.344
Not Black or white	0.0402	0.196	0.0464	0.210
Any Months on HMO	0.0291	0.168	0.0409	0.198
Diabetes	0.170	0.376	0.175	0.380
Malignant Neoplasm	0.506	0.500	0.464	0.499
Non-Malignant Neoplasm	0.242	0.428	0.327	0.469
BMI30+	0.0386	0.193	0.0300	0.171
History of Cancer	0.104	0.305	0.0763	0.265
Uterine Fibroid	0.239	0.427	0.287	0.452
Endometriosis	0.103	0.304	0.113	0.317
Pelvic Organ Prolapse	0.107	0.309	0.0745	0.263
Female Genital Bleeding	0.108	0.311	0.129	0.335
Postmenopausal Bleeding	0.113	0.317	0.0996	0.299
Other Ovarian Cyst	0.0752	0.264	0.0849	0.279
Female Genital Pain	0.135	0.342	0.128	0.334
Pelvic peritoneal adhesions	0.0989	0.299	0.100	0.300
Zip Percent White	0.798	0.203	0.792	0.221
Zip Percent College	0.382	0.173	0.336	0.154
Zip Percent Public Cash or Nutrition Assistance	0.114	0.0867	0.132	0.0885
Zip Median Household Income	59280.7	25358.6	53300.0	21594.2
Hospital Num. Hyst.s	62.70	44.14	52.37	44.51
Hospital Quality Measure: Proper Clot Prevention	0.878	0.0889	0.861	0.106
Hospital Quality Measure: Proper Antibiotic Use	0.913	0.0764	0.907	0.0872
Hospital Patient Satisfaction Score	2.549	0.115	2.534	0.117

Means for continuous variables and prevalence rates for indicator variables across hysterectomy patients, by type of hysterectomy. These procedure-level statistics describe hysterectomy outcomes, the demographic and clinical characteristics of the patients, the Zip codes of the patients' residences, and the hospitals where the procedures were performed. LOS is length of stay, MSA is Metropolitan Statistical Area, HMO is Medicare Advantage, and BMI 30+ is an indicator for Body Mass Index equalling or exceeding 30 (indicating obesity).

## 5 Empirical Strategy

In this section, I describe the excluded instrument that I use to identify the local average treatment effect and the marginal treatment effects. Next, I present the estimation methods and models. I consider the estimates of the local average treatment effects to be my main estimation strategy. Marginal treatment effect estimation requires estimating from smaller cells of data, so it is less precise than the two-stage least squares estimation. I consider the marginal treatment effects to constitute confirmatory, suggestive evidence. This section also shows I use the local and marginal effects to estimate the marginal rate of substitution.

### 5.1 Instrumental Variable Definition and Validity

In order to identify the marginal treatment effects or the local average treatment effect, I need an instrumental variable that affects the choice of hysterectomy approach but is excluded from the outcome models. The excluded instrument I use,  $Z$ , is

$$Z = T_L - T_A \tag{26}$$

the difference between the distance to a patient’s nearest hysterectomy-performing hospital that performs laparoscopic surgery and the distance to her nearest hospital performing hysterectomy. This instrument meets the three criteria for the two-stage least squares estimator to identify the local average treatment effect among the compliers: relevance, exclusivity, and monotonicity (Imbens and Angrist, 1994; Angrist, Imbens and Rubin, 1996; Imbens and Rubin, 1997). Statistical inference of the results also requires that the instrument is not weak. To estimate marginal treatment effects, as well, instruments must satisfy relevance (or, the rank condition), exclusivity (or, independence), and monotonicity (or, uniformity) (Heckman, Urzua and Vytlačil, 2006).

First, I show evidence from the first stage that the instrument is relevant and not weak. I estimate the conditional correlation of  $Z$  and  $D_L$ , the indicator for whether the hysterectomy was performed laparoscopically, on all total hysterectomies in 2007 and 2008, when few robotically assisted hysterectomies were performed.

Appendix Table 8 presents the first stage results. Across all specifications, the instrument is very stable and suggests that reducing the difference between the distance to the nearest laparoscopic hospital and the distance to the nearest hospital without laparoscopic surgery by 10 miles – i.e., making the nearest laparoscopic hospital closer relative to the nearest hospital without – increases the compliers’ likelihood to

undergo laparoscopic rather than abdominal hysterectomy by 0.5 percentage points. In each specification, the effective  $F$  statistic far exceeds the critical values.<sup>15</sup>

Second, the instrument arguably satisfies the exclusion restriction. A patient’s relative distance to a hospital performing laparoscopic surgery arguably affects hysterectomy outcomes only through its effect on the patient’s choice of hospital and whether that hospitals perform laparoscopic surgery. If relative distance were associated with demographic and clinical characteristics, the validity of this assumption would be in doubt. However, [Table 7](#) shows that patients in the top half of the relative distance instrument’s distribution have similar demographic and clinical characteristics as patients in the bottom half of the distribution. Further, [Table 8](#) shows that the first-stage point estimate is remarkably stable after adding many covariates to the model. While this does not preclude the existence of an unobserved characteristic caused by relative distance that in turn affects patients’ potential outcomes, the extensive list of covariates the result is robust to instills confidence that the instrument’s effect on outcomes is exclusively through its effect on the surgical mode choice.

Third, the instrument likely satisfies monotonicity and uniformity. Increasing the relative distance to a laparoscopic hospital arguably weakly decreases the patient’s propensity to undergo laparoscopic surgery, as opposed to abdominal surgery, and in no case would not increase the propensity. This is demonstrated in the Appendix in [Table 9](#). I estimate the first stage on several cells of patients by demographics and by diagnoses, following an approach used in the “judge IV” literature (e.g., [Arnold, Dobbie and Yang, 2018](#); [Bhuller, Dahl, Løken and Mogstad, 2020](#)) and in [Chan, Card and Taylor \(2022\)](#). In each case, the estimated effect of the distance instrument on the choice of laparoscopic hysterectomy is qualitatively the same and quantitatively similar, strongly suggesting that there are no defiers of the instrument, and the local average treatment effect identifies the treatment effect among the compliers only.

## 5.2 Estimation

This subsection presents the estimation methods used to estimate the local average treatment effects and the marginal treatment effects.

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<sup>15</sup>Following the advice of [Andrews, Stock and Sun \(2019\)](#), I conduct a weak instrument test that is robust to heteroskedasticity proposed by [Montiel Olea and Pflueger \(2013\)](#) and implemented by [Pflueger and Wang \(2015\)](#). Their test statistic is compared against a two-stage least squares/limited information maximum likelihood critical value either for 5% bias, which is 37.418 in my sample, or the value for 10% bias, which is 23.109. When there is just one endogenous variable, as in my case, the Olea-Montiel Pflueger test statistic is equivalent to the [Kleibergen and Paap \(2006\)](#) statistic. This latter test is packaged with the common Stata commands `ivreg2` and [Correia \(2018\)](#)’s `ivreghdfe`. Evidence strongly suggests that my instrument is not weak. However, note that [Andrews, Stock and Sun \(2019\)](#) advise that even if a set of instruments should fail the appropriate test, that the instrument should not be discarded due to its weakness. Instead, they write that analysis with the instrument should proceed with weak instrument-robust inference methods.



### 5.2.1 Estimating Local Average Treatment Effects

I estimate the local average treatment effect using a two-stage least squares estimator, where the first and second stages are

$$Y = \rho_{Y,0} + \rho_{Y,1}D_L + \rho_{Y,2}X + \epsilon_Y \quad (27)$$

$$D_L = \pi_0 + \pi_1Z + \pi_2X + \nu \quad (28)$$

where  $D_L$  is a random indicator for whether a hysterectomy was performed laparoscopically (rather than abdominally),  $Z$  is the excluded instrument described above that characterizes how much farther the nearest laparoscopic hospital is to a patient than the nearest hospital,  $X$  is a random vector of covariates, and  $Y$  is random variable representing a clinical outcome of the hysterectomy. In alternative regression specifications, the outcome is an indicator for whether the surgery resulted in any 90-day all-cause readmission, and an indicator for whether the hysterectomy inpatient stay was 2 or more days. The random variables  $\nu$ ,  $\epsilon_R$ , and  $\epsilon_S$  represent idiosyncratic shocks. I list the demographic, clinical Zip-level, and hospital covariates in [Section 4](#). I model the standard errors of two-stage least squares estimators assuming that there is clustering of outcomes at the hospital level.

### 5.2.2 Estimating Marginal Treatment Effects across Heterogeneous Patients

I estimate the marginal treatment effects using the two common estimation methods, the local instrumental variables method and the separate method. The marginal treatment effect can be re-written as:

$$\mathbb{E}[Y_L - Y_A|X = x, U_D = u_D] = \kappa_{L,Y}x - \kappa_{A,Y}x + \mathbb{E}[W_{Y,L} - W_{Y,A}|U_D = u_D] \quad (29)$$

for outcome  $Y$ , which alternatingly is the long length of stay indicator or the readmission indicator.  $W_{Y,L}$  and  $W_{Y,A}$  are the idiosyncratic shocks to potential outcomes  $Y_L$ , under  $L$ , and  $Y_A$ , under  $A$ , respectively. Each method involves estimating an outcome model that includes an additively separable component that represents unobserved heterogeneity:

$$\mathbb{E}[Y|X = x, U_D = u_D] = \kappa_{A,Y}x + px(\kappa_{L,Y} - \kappa_{A,Y}) + K_Y(p) \quad (30)$$

where  $K_Y(p) = p\mathbb{E}[W_{Y,L} - W_{Y,A}|U_D \leq p]$ , the unobserved “essential heterogeneity” in the outcome that is correlated with the potential utilities under each alternative.<sup>16</sup> The true distribution of  $K_Y(p)$  is unknown, and the function  $K_Y(p)$  could be nonlinear. Thus, the outcome is alternatively modeled parametrically in terms of the unobserved term and semiparametrically (partially linear), in keeping with practices in the literature. The four parametric specifications are (1) modeling  $K_Y(p)$  as Normal, (2 – 4) modeling  $k_Y(p) = K'(p)$  as a first-, second-, and then third-degree polynomial in  $p$ .

The semiparametric specifications model  $Y$  as an additively separable model of two components, (1) a nonlinear function of  $p$ ,  $K_Y(p)$ , and (2) the linear combination  $\kappa_{A,Y}X + pX(\kappa_{L,Y} - \kappa_{A,Y})$ . Estimation of  $K_Y(p)$  proceeds as follows. The residuals  $\hat{e}_Y$ ,  $\hat{e}_X$ , and  $\hat{e}_{Xp}$  are acquired by regressing  $Y$ ,  $X$ , and  $Xp$  each on  $p$  by local linear regression with the Epanechnikov kernel and alternative bandwidths of 0.01, 0.02, 0.03, and 0.05. The double residual regression is due to [Robinson \(1988\)](#) and modified by [Heckman, Ichimura and Todd \(1997\)](#). Next, the  $\kappa_{A,Y}$  and  $\kappa_{L,Y}$  are estimated by regressing  $\hat{e}_Y$  on  $\hat{e}_X$  and  $\hat{e}_{Xp}$ .  $Y - X\hat{\kappa}_A - X(\hat{\kappa}_L - \hat{\kappa}_A)p$  is in turn regressed on  $p$  by second-degree local polynomial regression with the Epanechnikov kernel and the bandwidth chosen by a plug-in estimator for a rule by [Fan and Gijbels \(1995\)](#). This yields  $\hat{K}_Y(p)$ , whose derivative is taken to construct the marginal treatment effect with the estimates for the kappas. A detailed description of this is in the appendix of [Heckman, Urzua and Vytlačil \(2006\)](#).

Because the unobserved heterogeneity is a function of the propensity score, each method entails estimating a propensity score for undergoing laparoscopic surgery, as opposed to undergoing abdominal surgery, as a probit function of covariates and the excluded instrument. The marginal treatment effects are only identified where there is overlap of the instrument-induced propensity scores. I model the propensity score as a probit of almost the entire set of covariates used in the ordinary least squares and two-stage least squares regressions.<sup>17</sup>

The local instrumental variable method due to [Heckman and Vytlačil \(1999\)](#) and [Heckman and Vytlačil \(2007\)](#) is to estimate  $\mathbb{E}[Y|x, p]$  using one of the parametric or semiparametric models described above and take the derivative with respect to the propensity score,  $p$ .

In the so-called separate approach developed by [Heckman and Vytlačil \(2007\)](#) and [Brinch, Mogstad and Wiswall \(2017\)](#), the terms reflecting unobserved heterogeneity and the coefficients from the two separate potential outcome models

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<sup>16</sup>Recall that  $p = P(Z, X)$  is the propensity score induced by relative distance instrument  $Z$  and  $U_D$  is the patient’s percentile of unobserved resistance to the laparoscopic alternative.

<sup>17</sup>Hospital quality measures were not available for all hospitals in my dataset. In the interest of maintaining the sample size for the information-intensive marginal treatment effect estimation, I omit these variables from the set of covariates in this section of analysis.

$$\mathbb{E}[Y_L|X = x, U_D = u_D] = \kappa_{L,Y}x + K_L(p) \quad (31)$$

$$\mathbb{E}[Y_A|X = x, U_D = u_D] = \kappa_{A,Y}x + K_A(p) \quad (32)$$

are estimated separately among laparoscopic patients and among abdominal patients, respectively. Then the marginal treatment effect at  $p$  is calculated by subtracting the two estimated potential outcomes at mean  $x$ .

I implement both the local instrumental variable method and the separate method using software by [Andresen \(2018\)](#). I estimate cluster-robust standard errors through 100 bootstrap repetitions with resampling over the hospitals ([Cameron and Trivedi, 2005](#)).

### 5.3 Marginal Rate of Substitution: Estimation and Inference

The model in [Section 3](#) shows that the marginal rate of substitution among patients with resistance to laparoscopic surgery  $u_D$  is identified by [Equation 20](#), the ratio of the marginal treatment effect on readmissions to the effect on length of stay. Thus, I estimate the marginal rate of substitution by estimating the marginal treatment effects and plug in:

$$\widehat{MRS}(\bar{x}, u_D) = \frac{\widehat{MTE}_R(\bar{x}, u_D)}{\widehat{MTE}_S(\bar{x}, u_D)} \quad (33)$$

If the indifference curves are linear, as postulated, or if they are convex but patients under a particular alternative of surgical technology are each located on the same relative point on their respective indifference curves, then these rates will be the same across all percentiles of resistance,  $u_D \in U_D$ .

I calculate the standard errors of this marginal rate of substitution with 100 bootstrap iterations.

I also estimate an approximation of the marginal rate of substitution by estimating the local average treatment effects on readmission and on length of stay and plugging in:

$$\widehat{MRS} \approx \frac{\frac{\hat{\psi}_1^R}{\hat{\pi}_1}}{\frac{\hat{\psi}_1^S}{\hat{\pi}_1}} \quad (34)$$

where  $\hat{\pi}_1$  is the estimate of the first-stage coefficient representing the effect of  $Z$  on  $D_L$ , and  $\hat{\psi}_1^R$  and  $\hat{\psi}_1^S$  are the intent to treat effects from the reduced form estimating equations for readmission and for length of stay, respectively.

I calculate standard errors on this estimate of the marginal rate of substitution in [Equation 34](#) using the Delta method.

## 6 Empirical Results

### 6.1 Testing the Model Predictions for Average Patients

The model predicts in [Equation 23](#) that the average length of stay among laparoscopic patients will be less than that among abdominal patients, conditional on covariates. I estimate the difference in conditional expectations of the chance of a long length of stay using ordinary least squares regression.

[Table 2](#) shows the OLS estimates of the effect of laparoscopic surgery (relative to abdominal surgery) on length of stay of 2 days or more under several specifications that each add additional covariates to control for potential confounding from patient and provider characteristics, as well as a fourth, fixed effect specification. The first specification has no covariates. The second controls for demographic covariates, the third adds comorbidities and gynecological conditions, the fourth adds characteristics of the residents in the patient’s Zip code, and the fifth adds hospital characteristics. [Section 4](#) lists the specific covariates in each category.

Laparoscopic hysterectomy patients have between a 41 percentage point and a 46 percentage point lesser chance of a length of stay that is 2 days or longer. This is in keeping with the model’s prediction of shorter mean lengths of stay among laparoscopic patients. The point estimate is fairly stable across the different specifications.

The model predicts that whether abdominal patients or laparoscopic patients have lower or higher mean readmission rates is ambiguous. [Table 3](#) shows that OLS and FE estimates of the association between laparoscopic surgery and any 90-day all-cause readmission is a reduction of about 4 to 8 percentage points. The estimate is also very stable across specifications.

**Table 2:** Association between Laparoscopic Procedure and Probability of Length of Stay of 2 or More Days: OLS and FE Regression

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Laparoscopic	-0.459*** (0.0137)	-0.459*** (0.0137)	-0.459*** (0.0138)	-0.461*** (0.0137)	-0.468*** (0.0141)	-0.459*** (0.0130)	-0.418*** (0.0166)
Observations	60889	60889	60889	59656	52368	59369	47158
Dependent variable mean	0.952	0.952	0.952	0.952	0.951	0.952	0.952
Demographic Controls		✓	✓	✓	✓	✓	✓
Clinical Controls			✓	✓	✓	✓	✓
Zip Code Controls				✓	✓	✓	✓
Hospital Controls					✓		
Fixed Effects						HSA	Hospital, Doc
$F$	1117.7	234.9	86.40	69.22	57.71	73.89	37.55
Adj. $R^2$	0.277	0.281	0.285	0.286	0.297	0.298	0.354

Standard errors in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

Ordinary least squares and fixed effects regression estimates of the difference between laparoscopic and abdominal hysterectomies in prevalence of a length of stay being two or more days. Demographic controls: whether the patient is Black, a race other than white or Black, under 65 years of age, or over 74 years of age. Clinical controls: the Charlson comorbidity index and indicators for whether the patient had diabetes, malignant neoplasm, non-malignant neoplasm, body mass index of 30 or over (considered obese), history of cancer indicated on the hysterectomy claim, uterine fibroids, endometriosis, pelvic organ prolapse, female genital bleeding, post-menopausal bleeding, an ovarian cyst, female genital pain, or peripheral adhesions. Zip code controls of the patient's residence: white percent of residents, the college-educated percent of residents, the percent of residents with public assistance (including cash or nutritional assistance), the median household income, and the percent of residents on Medicaid. Hospital controls: number of hysterectomies the hospital performed that year, a quality measure on the appropriate use of antibiotics, a quality measure on the prevention of blood clots in heart patients, and the overall Consumer Assessment of Healthcare Providers & Systems (CAHPS) score. HSA = Hospital Service Area. Doc = operating physician.

**Table 3:** Association between Laparoscopic Procedure and Probability of All-Cause 90-Day Readmission: OLS and FE Regression

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Laparoscopic	-0.0428*** (0.00570)	-0.0425*** (0.00563)	-0.0437*** (0.00577)	-0.0449*** (0.00591)	-0.0450*** (0.00624)	-0.0495*** (0.00610)	-0.0882*** (0.00885)
Observations	60889	60889	60889	59656	52368	59369	47158
Dependent variable mean	0.162	0.162	0.162	0.162	0.161	0.162	0.164
Demographic Controls		✓	✓	✓	✓	✓	✓
Clinical Controls			✓	✓	✓	✓	✓
Zip Code Controls				✓	✓	✓	✓
Hospital Controls					✓		
Fixed Effects						HSA	Hospital, Doc
$F$	56.50	42.30	73.35	58.56	49.63	54.41	32.21
Adj. $R^2$	0.000790	0.00482	0.0290	0.0293	0.0310	0.0343	0.00907

Standard errors in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ 

Ordinary least squares and fixed effects regression estimates of the difference between laparoscopic and abdominal hysterectomies in prevalence of a 90-day all-cause readmission. Demographic controls: whether the patient is Black, a race other than white or Black, under 65 years of age, or over 74 years of age. Clinical controls: the Charlson comorbidity index and indicators for whether the patient had diabetes, malignant neoplasm, non-malignant neoplasm, body mass index of 30 or over (considered obese), history of cancer indicated on the hysterectomy claim, uterine fibroids, endometriosis, pelvic organ prolapse, female genital bleeding, post-menopausal bleeding, an ovarian cyst, female genital pain, or peripheral adhesions. Zip code controls of the patient's residence: white percent of residents, the college-educated percent of residents, the percent of residents with public assistance (including cash or nutritional assistance), the median household income, and the percent of residents on Medicaid. Hospital controls: number of hysterectomies the hospital performed that year, a quality measure on the appropriate use of antibiotics, a quality measure on the prevention of blood clots in heart patients, and the overall Consumer Assessment of Healthcare Providers & Systems (CAHPS) score. HSA = Hospital Service Area. Doc = operating physician.

## 6.2 Testing the Model Predictions for Marginal Patients

Next, I test the model’s assumptions and predictions about marginal patients. The theoretical model in [Section 3](#) assumes that laparoscopic procedures have shorter lengths of stay than abdominal procedures among marginal patients, and it predicts in [Equation 49](#) that laparoscopic procedures have greater readmission rates than abdominal procedures among marginal patients.

[Table 4](#) presents the two-stage least squares estimates of the local average treatment effects on whether a hysterectomy patient has a length of stay of two days or more. Across specifications, the estimated effect is negative and statistically significant. The magnitude of the effect is greater as more factors are controlled for. Column 5 shows that controlling for all covariates, laparoscopic hysterectomy causes a 57 percentage point decline in the chance of a length of stay of two or more days, relative to abdominal hysterectomy, among patients who are induced into the laparoscopic mode by the relative distance instrument’s variation.

Estimates of the local treatment effects on the chance of a readmission are shown in [Table 5](#). Across specifications, the estimated effect on readmissions is positive and economically significant. It is statistically significant controlling for demographic, clinical and Zip-code level socioeconomic factors. When hospital factors – including some Hospital Compare quality measures which are not available for all hospitals – are additionally controlled for, the point estimate is low enough and the standard errors are large enough that the estimate is statically insignificant. I conclude from this evidence that there is good reason to believe that compliers experience greater readmission risk under laparoscopic hysterectomy than under abdominal hysterectomy.

My study in its current form cannot explain why marginal laparoscopic hysterectomy patient experience greater readmission rates than marginal abdominal patients. One possibility is that marginal laparoscopic patients experience greater injury rates than inframarginal laproscopic patients and marginal abdominal patients. One metastudy suggests that laparoscopic patients have greater rates of bladder and ureter injuries than abdominal patients ([Teeluckdharry et al., 2015](#)). Indeed, I find that evidence that marginal laparoscopic hysterectomy patients experience greater rates of readmissions in which it was indicated they had urogenital infections ([Table 10](#) in [Appendix D](#)), which are associated with such injuries.

In sum, these results are consistent with the model’s assumptions and predictions for marginal patients: the two-stage least squares procedures estimate that the chance of a hysterectomy having a long length of stay is greater among marginal abdominal patients than among marginal laparoscopic patients, and the chance of a readmission is greater among marginal laparoscopic patients than among marginal abdominal patients.

**Table 4:** Effect of Laparoscopic Procedure on the Probability of Length of Stay is 2 or More Days: 2SLS

	(1)	(2)	(3)	(4)	(5)
Laparoscopic	-0.332*** (0.0681)	-0.397*** (0.0644)	-0.443*** (0.0635)	-0.542*** (0.0950)	-0.567*** (0.109)
Observations	54998	54998	54998	54978	48559
Dependent Variable Mean	0.950	0.950	0.950	0.950	0.949
Demographic Controls		✓	✓	✓	✓
Clinical Controls			✓	✓	✓
Zip Code Controls				✓	✓
Hospital Controls					✓
$F$	23.80	56.05	27.98	24.05	21.90
Adj. $R^2$	0.260	0.281	0.290	0.283	0.289
First-Stage Effective $F$	94.38	102.0	104.4	60.39	43.89

Standard errors in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

Two-staged least squares estimates, using relative distance to hospital with laparoscopic surgery as instrument. Across specifications, the effective F statistic (due to [Montiel Olea and Pflueger \(2013\)](#) and [Kleibergen and Paap \(2006\)](#)) should be compared against either the two-stage least squares/limited information maximum likelihood critical value for 5% bias, which is 37.418, or for 10% bias, which is 23.109. Demographic controls: whether the patient is Black, a race other than white or Black, under 65 years of age, or over 74 years of age. Clinical controls: the Charlson comorbidity index and indicators for whether the patient had diabetes, malignant neoplasm, non-malignant neoplasm, body mass index of 30 or over (considered obese), history of cancer indicated on the hysterectomy claim, uterine fibroids, endometriosis, pelvic organ prolapse, female genital bleeding, post-menopausal bleeding, an ovarian cyst, female genital pain, or peripheral adhesions. Zip code controls of the patient's residence: white percent of residents, the college-educated percent of residents, the percent of residents with public assistance (including cash or nutritional assistance), the median household income, and the percent of residents on Medicaid. Hospital controls: number of hysterectomies the hospital performed that year, a quality measure on the appropriate use of antibiotics, a quality measure on the prevention of blood clots in heart patients, and the overall Consumer Assessment of Healthcare Providers & Systems (CAHPS) score.



**Table 5:** Effect of Laparoscopic Procedure on the Probability of Any 90-day Readmission: 2SLS

	(1)	(2)	(3)	(4)	(5)
Laparoscopic	0.526*** (0.128)	0.452*** (0.119)	0.298*** (0.112)	0.361** (0.163)	0.173 (0.191)
Observations	54998	54998	54998	54978	48559
Dependent Variable Mean	0.163	0.163	0.163	0.163	0.162
Demographic Controls		✓	✓	✓	✓
Clinical Controls			✓	✓	✓
Zip Code Controls				✓	✓
Hospital Controls					✓
$F$	16.86	31.30	66.98	52.63	47.40
Adj. $R^2$	-0.148	-0.107	-0.0235	-0.0446	0.00960
First-Stage Effective $F$	94.38	102.0	104.4	60.39	43.89

Standard errors in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

Two-staged least squares estimates, using relative distance to hospital with laparoscopic surgery as instrument. Across specifications, the effective F statistic (due to [Montiel Olea and Pflueger \(2013\)](#) and [Kleibergen and Paap \(2006\)](#)) should be compared against either the two-stage least squares/limited information maximum likelihood critical value for 5% bias, which is 37.418, or for 10% bias, which is 23.109. Demographic controls: whether the patient is Black, a race other than white or Black, under 65 years of age, or over 74 years of age. Clinical controls: the Charlson comorbidity index and indicators for whether the patient had diabetes, malignant neoplasm, non-malignant neoplasm, body mass index of 30 or over (considered obese), history of cancer indicated on the hysterectomy claim, uterine fibroids, endometriosis, pelvic organ prolapse, female genital bleeding, post-menopausal bleeding, an ovarian cyst, female genital pain, or peripheral adhesions. Zip code controls of the patient's residence: white percent of residents, the college-educated percent of residents, the percent of residents with public assistance (including cash or nutritional assistance), the median household income, and the percent of residents on Medicaid. Hospital controls: number of hysterectomies the hospital performed that year, a quality measure on the appropriate use of antibiotics, a quality measure on the prevention of blood clots in heart patients, and the overall Consumer Assessment of Healthcare Providers & Systems (CAHPS) score.

### 6.3 Estimation of the Marginal Rate of Substitution from Two-Stage Least Squares

Here I estimate the marginal rate of substitution of a greater chance of a long length of stay for a lesser chance of a readmission, by taking the ratio of the local effect on readmissions to the local effect on length of stay (Equation (34)). The estimates under different outcome model specifications are listed in Table 6. In the specifications controlling demographic and clinical characteristics as well as the specification additionally controlling for characteristics of the patients' neighborhoods, I estimate the marginal rate of substitution to be around -0.67. In the fifth specification, where the effect is estimated to be less and with greater uncertainty, the estimate of the marginal rate of substitution is -0.23.

**Table 6:** Estimates of the marginal rate of substitution from two-stage least squares

	(1)	(2)	(3)	(4)	(5)
MRS	-1.585*** (0.504)	-1.138*** (0.354)	-0.673** (0.277)	-0.666** (0.334)	-0.305 (0.359)
Observations	54998	54998	54998	54978	48559
Demographic Controls		✓	✓	✓	✓
Clinical Controls			✓	✓	✓
Zip Code Controls				✓	✓
Hospital Controls					✓

Standard errors in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

Estimates of the marginal rate of substitution of a greater chance of a long length of stay for a lesser chance of a readmission. They are calculated by dividing the two-stage least squares estimate of the local average treatment effect on the probability of a patient's length of stay being 2 or more days (relative to abdominal surgery) by the two-stage least squares estimate of the local effect on the probability of an all-cause 90-day readmission. Standard errors were calculated by the Delta method. The model in Column 5 includes quality measures from Hospital Compare which are not available for all hospitals.

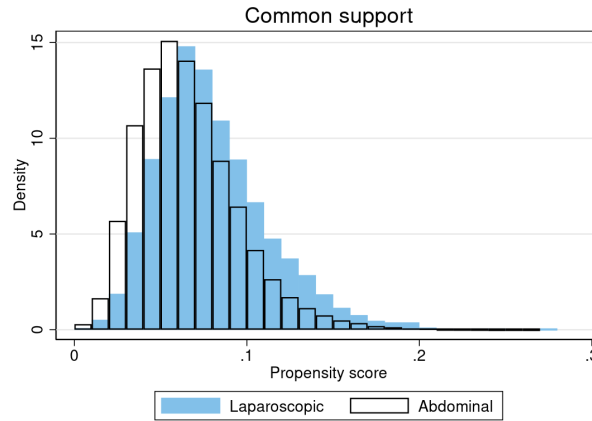
The results from the fifth specification with all covariates implies that patients are willing to trade off a 55 percentage point increase in the chance of long length of stay for a 17 percentage point decrease in the probability of a readmission. The standard errors of the marginal rate of substitution estimate are calculated by the Delta method and are presented in the parentheses.

### 6.4 Estimation of Marginal Treatment Effects across Heterogeneous Patients

In this section, I test the model's predictions about outcomes among marginal patients through estimation of marginal treatment effects of laparoscopic surgery, as opposed to abdominal surgery, on readmission and on length of stay among patients with a given level of unobserved "cost" or "resistance" to the laparoscopic

option, which the theory section showed is partially dependent on the patient complexity characteristic,  $\theta$ . I estimate these effects for different levels of unobserved resistance to laparoscopic surgery.

The propensity score as a function of observable covariates and excluded instruments is integral to the estimation of marginal treatment effects. The marginal treatment effects are identified only for propensity scores that are induced by the variation in the available instrument and that are observed under both surgical options. Figure 4 presents the distributions of propensity scores, generated from a probit regression, among laparoscopic patients and among abdominal patients. Much of the probability mass of the overlap of propensity score distributions under the two surgical alternatives is among propensity scores between five and ten percent, so the marginal treatment effects among patients with propensity scores outside that range are not identified.



**Figure 4:** Overlapping Distributions of Propensity Scores

Distributions of propensities scores among laparoscopic cases and abdominal cases. The local instrumental variable method and the separate method of estimating marginal treatment effects can identify where there is overlap of the propensity scores of the two groups.

The covariates  $X$  that I control for are the demographic controls, the clinical controls, the Zip code-level controls, and one of the hospital controls, the number of hysterectomies that the hospital performed that year. I omit the remaining the hospital controls, the quality measures from Medicare’s Hospital Compare program, because they are not available for all hospitals and thus their inclusion would reduce my sample of hysterectomies considerably.

The first two rows of Figure 6 graphically present estimates of marginal treatment effects on the probability of a length of stay being 2 or more days, with respect to the patient’s percentile of unobserved resistance to (or, net unobserved “cost” of) laparoscopic surgery as opposed to abdominal surgery. The effects are estimated by local instrumental variable method (row one) and by the separate method (row two). The first plot in the first row summarize the estimates from each of the parametric and semiparametric models

estimated. The estimates are very similar across models within estimation method. In the local instrumental variable method, estimates of the marginal effects across model specifications are about -0.5 among the patients most likely to undergo laparoscopic surgery. The effects among patients at the 15th percentile range from -1 to -2.5, with estimates from the parametric models sloping down more than the results from the semiparametric models.

These point estimates are quite large, but keep in mind the wide 95 percent confidence intervals, shaded in gray, particularly for percentiles of resistance with less support from the data. To give a sense of the variation in the estimations, plots in the second column present point estimates and 95% confidence intervals from the most restrictive model, the parametric model assuming that the unobserved heterogeneous component of the outcome,  $K_Y(p)$ , is Normal, and plots in the third column present results from the most flexible model, the semiparametric models with the narrowest bandwidth, 0.01. Estimates of the effects on length of stay are mostly significant at the 95% level.

As shown in the second row, the separate method estimates that the effects on length of stay among the patients at the 5th percentile range from about -0.4 to 0.6. Among patients at the 15th percentile, the estimates are between -0.7 and -0.9.

Across all models, the estimates suggest that the effects of laparoscopic surgery on length of stay are greater for patients with greater resistance to the laparoscopic alternative. However, the width of the confidence intervals relative to the downward slope of the point estimates make this finding merely suggestive. The full set of results on length of stay from the instrumental variable method and the separate method are in Appendix [Figure 11](#) and [Figure 13](#), respectively.

The third and fourth rows of [Figure 6](#) presents estimates of the marginal treatment effects on the chance of a readmission from the local instrumental variable method and the separate method, respectively. Across models, the local instrumental variable estimators in row 3 suggest that the effects of readmission are positive and increasing in unobserved resistance to laparoscopic surgery. At the 5th percentile of resistance, the estimates are clustered around an effect of 0.3, and at the 15th percentile, they range from 0.4 to 1.5. Economically, this fits with the prior finding that patients with greater resistance experience differential lengths of stay of greater magnitude under laparoscopic surgery: if patients who have greater resistance to laparoscopic surgery experience better laparoscopic treatment effects on lengths of stay than patients who are more willing to choose laparoscopic surgery, then those higher-resistance patients must experience worse outcomes under laparoscopic surgery on some other dimension than the lower-resistance patients. Statistically, these findings must be taken with caution as the 95% confidence intervals almost always include zero and are wide, particularly so for higher-resistance patients.

Estimates from the separate method tell a somewhat different story. While most of the estimates for the

range of percentiles of resistance that are most supported by the data, from the 5th to the 10th percentiles, are positive, the series of estimates from each model are flat or downward sloping. The effects are much smaller in magnitude than those estimated from the local instrumental variables, suggesting much more uncertainty as to the signs of the effects and the presence of an upward or downward slope. Evidence from the most restrictive and the most flexible models under separate estimation do not present strong evidence of a slope in the marginal rates of substitution over the most populated range of percentiles. The full set of results on readmissions from the instrumental variable method and the separate method are in Appendix [Figure 12](#) and [Figure 14](#), respectively.

In sum, there is strong evidence that patients experience lower lengths of stay under laparoscopic surgery than under abdominal surgery, and there is evidence that this effect could be declining in patient resistance to laparoscopic surgery. This raises the question of what relative outcome from laparoscopic surgery could be worsening as resistance increases that counterweights this declining relative length of stay. Estimates from local instrumental variable regression suggest that the risk of readmissions is greater under laparoscopic surgery and that this effect is greater among patients with greater resistance to laparoscopic surgery. This would be the countervailing consideration that makes laparoscopic surgery less attractive among patients with greater resistance. It also is consistent with the evidence from the two-stage least squares procedures, which is no surprise since the local average treatment effect is a weighted combination of the marginal treatment effects, and the weights are all positive because the instrument satisfies monotonicity, or, uniformity. (See Appendix [Figure 15](#) for the estimated weights at each percentile of unobserved resistance.) Evidence from the separate method that laparoscopic surgery results in greater readmission risk is weak, but the separate method estimates all the effects twice, once among laparoscopic patients and once among abdominal patients, while the local instrumental variable method performs this once. Therefore, it's possible that the separate method is underpowered.

## 6.5 Estimation of the Marginal Rate of Substitution Using Marginal Treatment Effects

This section attempts to estimate the marginal rate of substitution at different percentiles of resistance using a ratio of marginal treatment effects, as in [Equation 21](#). I divide the estimated marginal effect on having a readmission by the estimated marginal effect on having a length of stay of two or more days, and I plot the results over the resistance.

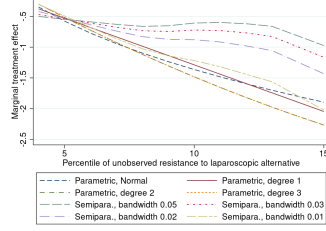
For brevity, I present estimates of marginal rates of substitution from the most restrictive model and the most flexible model estimated by local instrumental variable. In [Figure 7](#), (a) plots estimates of the effect on

readmission, the effect on length of stay, and the marginal rate of substitution from the model assuming that the unobserved component has a Normal distribution. The 95 percent confidence intervals on the estimates of the marginal rate of substitution are represented by the gray regions. The marginal rate of substitution is estimated to be -0.5 at the 5th percentile and to slope downward slightly to -0.6 at the 14th percentile. Subfigure (b) plots results from the semiparametric model with a bandwidth of 0.01. The marginal rate of substitution is estimated to be -0.5 at the 5th percentile and slopes down to -0.8 at the 14th percentile.

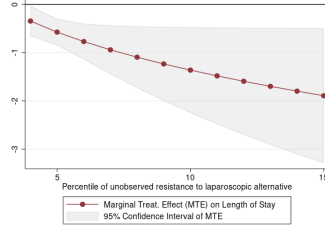
The separate estimates from the restrictive, Normal model are stable, from -0.2 to -0.1. The estimates from the most flexible model are nonmonotonic and volatile, ranging from -0.8 at the 5th percentile to 0.6 at the 14th. The full set of estimates of the marginal rate of substitution are in Appendix [Figure 16](#). In no cases are the marginal rates of substitution statistically significantly different from zero, which follows from the estimates of the marginal treatment effects on readmissions being statistically insignificant.

**Figure 6: Summary of Marginal Treatment Effect Estimates**

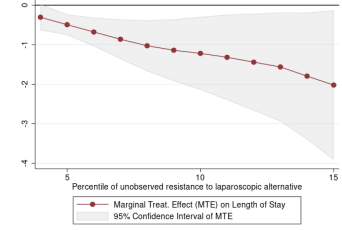
**Effect on Probability of Length of Stay of 2 or More Days, Local Instrumental Variable Method**



(a) Local instrumental variable estimates from all length of stay models.

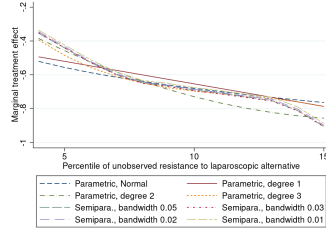


(b) Parametric: Normal.

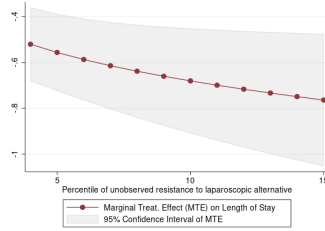


(c) Semiparametric: bandwidth 0.01.

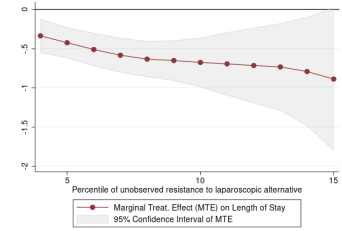
**Effect on Probability of Length of Stay of 2 or More Days, Separate Method**



(d) Separate method estimates from all length of stay models.

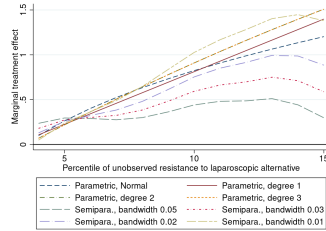


(e) Parametric: Normal.

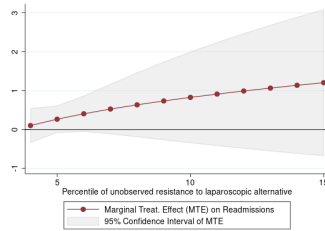


(f) Semiparametric: bandwidth 0.01.

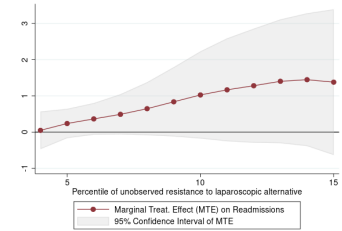
**Effect on Probability of All-Cause 90-Day Readmission, Local Instrumental Variable Method**



(g) Local instrumental variable method estimates from all readmission models.

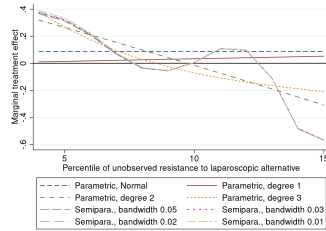


(h) Parametric: Normal.

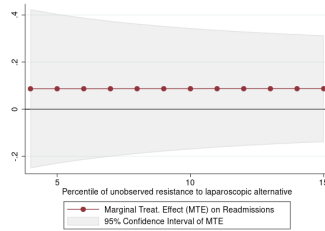


(i) Semiparametric: bandwidth 0.01.

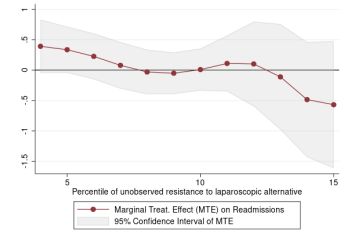
**Effect on Probability of All-Cause 90-Day Readmission, Separate Method**



(j) Separate method estimates from all readmission models.



(k) Parametric: Normal.

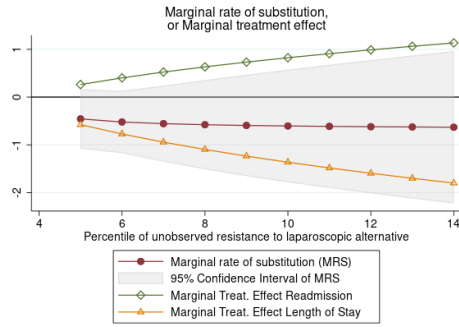


(l) Semiparametric: bandwidth 0.01.

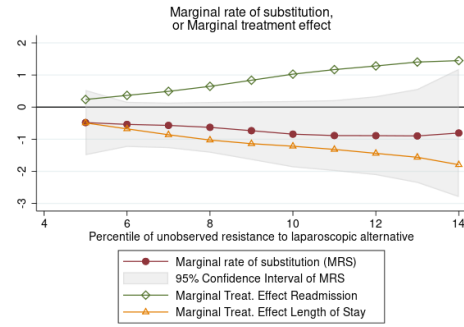
The horizontal axis in each plot is  $U_D$ , the case's percentile on the distribution of unobserved “resistance” to or “cost” of the laparoscopic choice. Gray bands are 95% confidence intervals, bootstrapped with 100 repititions. Parametric models presented in middle column model unobserved heterogeneity (functions of the propensity score) as Normal. Semiparametric models in right column model the unobserved heterogeneity with a local polynomial using the Epanechnikov kernel.

**Figure 7:** Marginal Rates of Substitution across Heterogeneous Patients, Calculated from Marginal Treatment Effects

### Local Instrumental Variable Method

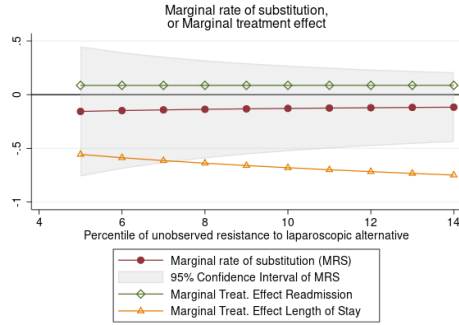


(a) Estimates from Normal Parametric Model

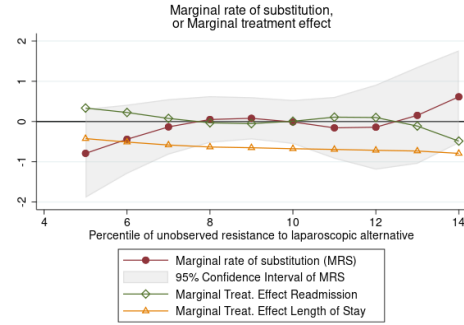


(b) Estimates from Semiparametric Model

### Separate Method



(c) Estimates from Normal Parametric Model



(d) Estimates from Semiparametric Model

Estimates of the marginal rate of substitution of readmission risk for length of stay, at each percentile of unobserved “resistance” to or “cost” of the laparoscopic approach. Also plotted are the bootstrapped 95% confidence intervals of the marginal rates of substitution and the marginal treatment effects on readmission rates and on chance of a length of stay of 2 days or more. Semiparametric results come from the Epanechnikov filter with a 0.01 bandwidth. The marginal rate of substitution is calculated by dividing the marginal treatment effect on readmission by the marginal treatment effect on length of stay.



## 7 Robustness Checks

As a robustness check, Appendix [Table 11](#) presents the estimates for the local average treatment effect on length of stay being 3 or more days. The estimated effect in the specification with all controls is -0.5, although it is imprecisely estimated.

## 8 Conclusion

Medical technologies may present patients with tradeoffs between improvements on different dimensions of care. I have shown that hysterectomy patients on the margin between laparoscopic and abdominal surgery face a trade-off between shorter lengths of stay and greater readmission risk. I presented a Roy model in which patients and physicians choose surgical technology based on how it affects two clinical outcomes. The model predicts that indifferent patients and their physicians face shorter lengths of stay but greater readmission rates under laparoscopic surgery than abdominal surgery. These differences in outcomes among indifferent patients are identified by marginal treatment effects, which can be estimated for patients with different levels of unobserved resistance to the laparoscopic alternative. The local average treatment effects identified by two-stage least squares regressions are positively weighted averages of the marginal treatment effects across patient types. Empirically I find that compliers of a distance-based instrument for the choice of laparoscopic procedure experienced shorter lengths of stay under laparoscopic hysterectomy than under abdominal hysterectomy but also experienced greater readmission rates. The estimation of these local average treatment effects leads to an estimation of a ratio that equals patients' marginal rate of substitution of longer length of stay for lesser readmission risk if providers had no influence over treatment but more broadly reflects preferences and objectives in the health care system otherwise. The marginal treatment effect estimates suggest that the (negative, beneficial) effect on length of stay is greater in magnitude for patients with greater unobserved resistance to laparoscopic surgery, and some model specifications suggest that the (positive, detrimental) effect on readmission rates also increases in magnitude with respect to unobserved resistance to the laparoscopic alternative, although these marginal treatment effect estimates are imprecise.

Taking a wider view, this paper emphasizes the multidimensionality of technology. Technological innovation does not proceed along a single continuum and may lead to new products and services that prompt end users to make tradeoffs between different dimensions of quality, not just between quality and cost. When end users are heterogeneous, as in the case of hysterectomy patients with different diagnoses, different comorbidities, and different complexities, diffusion of new technologies may proceed unevenly or incompletely. In health care, understanding these tradeoffs is important to understanding the welfare impacts of new medical

technologies and to assessing their allocative efficiency.

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## A Theory: Derivations of Findings

### A.1 Choices by Patients with Different Levels of Complexity

This section shows how the utility functions under laparoscopic surgery and under abdominal surgery and the adverse outcome production functions affect choices among patients with, alternatively, low and high  $\theta$  types.

Consider the indifference curve of patient type  $\theta = 0$  for fixed  $Z$  (Figure 3a) in terms of  $S$  and  $R$ , conditional on  $X$  and  $T_j$ . Note that the slope of the indifference curve is  $m = -\frac{\omega_s}{\omega_R}$ , and bliss utility,  $T_j$ , and  $\omega_T$  are encoded in the indifference curve's  $R$ -intercept:

$$R(\theta) = \frac{u_B - \omega_T T_j}{\omega_R} - \frac{\omega_S}{\omega_R} S(\theta) \quad (35)$$

Each point represents a bundle of adverse clinical outcomes, and points  $L^0$  and  $A^0$  represent the bundles that type  $\theta = 0$  can achieve under the two production technologies available  $L$  and  $A$ , respectively. Highest utility is achieved at the origin, and utility declines as  $S$  or  $R$  increases. From the assumption that low complexity cases choose  $L$ , it follows that

$$U_L(0) < U_A(0) \quad (36)$$

$$-m = \frac{\omega_s}{\omega_R} < \frac{\delta_A - \delta_L}{\alpha_L - \alpha_A} \quad (37)$$

$$< \frac{\gamma_L - \gamma_A}{\alpha_L - \alpha_A} \quad (38)$$

The last line follows from

$$U_A(1) > U_L(1) \quad (39)$$

$$\gamma_A - \gamma_L < \delta_L - \delta_A \quad (40)$$

Inequality 38 implies that the bundles  $L^0$  and  $A^0$  be oriented relative to type 0's indifference curve as depicted in Figure 3a. Patients with the lowest complexity choose  $L$ , which yields lower  $S$  but higher  $R$  than  $A$ .

By analogous reasoning, patients with the highest complexity (type  $\theta = 1$ ) choose abdominal surgery

bundle  $A^1$ , which yields a lesser readmission risk but longer length of stay than  $L$  (Figure 3b).

## A.2 Comparative Advantage

Assuming that low- $\theta$  types choose laparoscopic surgery and high- $\theta$  types choose abdominal surgery, i.e.,  $U_L(\theta = 0) > U_A(\theta = 0)$  and  $U_A(\theta = 1) > U_L(\theta = 1)$  implies:

$$\omega_S(\alpha_L - \alpha_A) < \omega_R(\gamma_A - \gamma_L) \quad (41)$$

$$\omega_S(\underbrace{\alpha_A - \alpha_L}_{>0 \text{ by } S_A(\theta) > S_L(\theta) \forall \theta}) > \omega_R(\gamma_A - \gamma_L) \quad (42)$$

and

$$\omega_S(\beta_A - \beta_L) - \omega_R(\delta_L - \delta_A) < \omega(\alpha_L - \alpha_A) - \omega_R(\gamma_A - \gamma_L) < 0 \quad (43)$$

## A.3 Existence of A Type of Patient Who is Indifferent Conditional on Z

Consider the indifferent patient, conditioning on  $X$  and the idiosyncratic shocks. Setting the utility of laparoscopic surgery, as a function of  $\theta$  equal to the utility of abdominal surgery, substituting into the utility functions, , set equal to each other and solving for  $\theta$  yields:

$$\theta^* = \frac{\omega_R(\gamma_L - \gamma_A) + \omega_T Z - \omega_S(\alpha_A - \alpha_L)}{\omega_S(\beta_A - \beta_L) - \omega_R(\delta_L - \delta_A)} \quad (44)$$

where  $\theta^*$  is the  $\theta^{LA}(Z)$  that makes a patient indifferent for a particular value of  $Z$ . The type of patients  $\theta$  who are indifferent at value  $Z$  is a linear function of  $Z$ , and as  $Z$  increases,  $\theta^*$  decreases:

$$\frac{\partial \theta^*}{\partial Z} = \frac{\omega_T}{\omega_S(\beta_A - \beta_L) - \omega_R(\delta_L - \delta_A)} < 0 \quad (45)$$

where the denominator is negative due to the findings derived from comparative advantage.

## A.4 Outcome Predictions on the Margin

Consider a particular combination of values of  $\theta$ ,  $T_L$ , and  $T_A$  such that a patient with those values is indifferent. Conditioning on  $X$ , there is one  $\theta$  for a given  $Z = T_L - T_A$  such that the patient is indifferent between procedures. Call this  $\theta^{LA}(Z) = \theta^*$ .



$$U_L(\theta^*, T_L) = U_A(\theta^*, T_A) \quad (46)$$

$$\frac{\omega_S}{\omega_R} (\alpha_L + \beta_L \theta^* - \alpha_A - \beta_A \theta^*) + \frac{\omega_T}{\omega_R} (Z) = (\gamma_A + \delta_A \theta^*) - (\gamma_L + \delta_L \theta^*) \quad (47)$$

If we assume that  $\alpha_L + \beta_L \theta < \alpha_A + \beta_A \theta$  for all values of  $\theta$ , because laparoscopic surgery is always less invasive than abdominal surgery, then the left hand side must be negative. So the right-hand side must be negative when  $Z = 0$ : the indifferent patient experiences a higher readmission rate under laparoscopic surgery than under abdominal surgery:

$$(\gamma_A + \delta_A \theta_{LA}) - (\gamma_L + \delta_L \theta_{LA}) < 0 \quad (48)$$

i.e.,

$$R_A(\theta_{LA}) - R_L(\theta_{LA}) < 0 \quad (49)$$

Substituting Equation (44) for  $\theta^*$  in Equation (47) and differentiating with respect to  $Z$  yields:

$$\frac{d[S_L(\theta^*) - S_A(\theta^*)]}{dZ} = \omega_T \left( \frac{\beta_L - \beta_A}{\omega_S(\beta_A - \beta_L) - \omega_R(\delta_L - \delta_A)} \right) \quad (50)$$

$$\frac{d[R_L(\theta^*) - R_A(\theta^*)]}{dZ} = \omega_T \left( \frac{\delta_L - \delta_A}{\omega_S(\beta_A - \beta_L) - \omega_R(\delta_L - \delta_A)} \right) \quad (51)$$

Substituting these into Equation (43) yields:

$$-\omega_S \frac{d[S_L(\theta^*) - S_A(\theta^*)]}{dZ} - \omega_R \frac{d[R_L(\theta^*) - R_A(\theta^*)]}{dZ} > 0 \quad (52)$$

One can see that both derivatives cannot be simultaneously positive.

## A.5 Predicted Difference in Mean Readmission Rates

Restating the difference in means between readmission rate among laparoscopic patients and among abdominal patients:

$$\bar{R}_L - \bar{R}_A \quad (53)$$

$$= \underbrace{\frac{1}{N_L} \left[ \sum_{\{i:\theta_i < \theta^*\}} R_i + \sum_{\{i:\theta_i = \theta_{LA} \& D_A=1\}} R_i \right]}_{\text{Average } R \text{ over inframarginal and marginal } L \text{ patients}} - \underbrace{\frac{1}{N_A} \left[ \sum_{\{i:\theta_i > \theta_{LA}\}} R_i + \sum_{\{i:\theta_i = \theta_{LA} \& D_A=1\}} R_i \right]}_{\text{Average } R \text{ among inframarginal and marginal } A \text{ patients}} \quad (54)$$

$$(55)$$

$$= \frac{1}{N_L} \left[ \sum_{\theta < \theta^*} (\gamma_L + \delta_L \theta_i) + N_{LA\&A} (\gamma_L + \delta_L \theta^*) \right] - \frac{1}{N_A} \left[ \sum_{\theta > \theta^*} (\gamma_A + \delta_A \theta_i) + N_{LA\&A} (\gamma_A + \delta_A \theta^*) \right] \quad (56)$$

It follows that  $\bar{R}_L - \bar{R}_A < 0$  if:

$$\frac{1 - N_{\theta^* \& L}}{N_L} \gamma_L - \frac{1 - N_{\theta^* \& A}}{N_A} \gamma_A + \frac{1}{N_L} \sum_{\theta < \theta^*} \delta_L \theta_i - \frac{1}{N_A} \sum_{\theta > \theta^*} \delta_A \theta_i < \frac{N_{\theta^* \& A}}{N_A} (\gamma_A + \delta_A \theta^*) - \frac{N_{\theta^* \& L}}{N_L} (\gamma_L + \delta_L \theta^*) \quad (57)$$

One case see from [Equation 57](#) that the sign of the difference in means is dependent on an interaction of the differences between technologies in readmission rates among patients without complications, in the degrees to which readmission rates increase with respect to  $\theta$ , and the shares of patients of each technology choice who are of different values of  $\theta$ .

The right-hand side is the difference in weighted readmissions rates among  $\theta_{LA}$ -type patients and among abdominal patients, where the weights are the indifferent shares of patients of a particular choice. The left-hand side is the difference in weighted readmission rates among  $\theta = 0$  types, where the weights are the inframarginal shares of patients of the respective technology choice, added to the difference in weighted average “complexity-sensitive” components of the readmission rates among inframarginal laparoscopic patients and among inframarginal abdominal patients, where the weights for a given patient type is that patient type’s share of patients undergoing the respective type of surgery, and where “extra” readmission component is  $\delta_j$ , the degree to which readmission rates increase under technology  $j$  with  $\theta$ .

Here one can see that whether the difference in means is positive or negative is not dependent on the sign of the treatment effect among the marginal patients, whose treatment effect would be approximated by the local average treatment effect. In other words, in this selection setting, theory allows for the sign of the local average treatment effect to be different from the sign of the ordinary least squares estimate of the treatment effect. This suggests departing from the conventional notion that a contradiction between the sign of the estimated local average treatment effect and the sign of the ordinary least squares estimate of the average

treatment effect is a cause for concern about the instrumental variable's validity. Theory predicts that the signs will be different under certain reasonable parameter assumptions and distributional assumptions.

Note that the finding about relative readmission rates among patients on the margin in [Equation 48](#) implies

$$\gamma_A - \gamma_L < (\delta_L - \delta_A)\theta^* \quad (58)$$

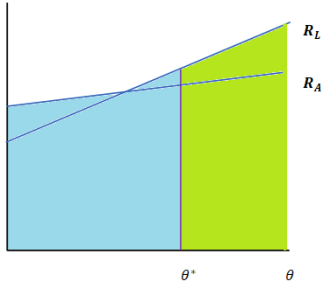
Consider three cases:

**Case 1:**  $\gamma_A - \gamma_L > 0$  . Then,  $\delta_L - \delta_A > 0$ . I.e., if readmission is worse for  $A$  than for  $L$  at  $\theta = 0$ , then readmissions must worsen faster, w.r.t.  $\theta$ , under  $L$  than under  $A$  in order for readmissions to be higher under  $L$  than under  $A$  for the  $\theta^*$  types.

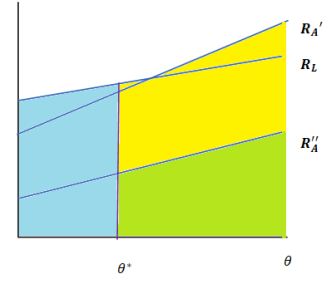
This is illustrated in [Figure 8a](#). The average readmission rate among laparoscopic patients is the integral of  $R_L$  times the patient population density w.r.t.  $\theta$ . The blue hatched area represents the average readmission rate if  $\theta \sim Uniform$ . The average readmission rate among abdominal patients under that distributional assumption is the green area. One can see that the average among laparoscopic patients relative to the average among abdominal patients rises if (1) the number of patients between the  $\theta$  such that  $R_L(\theta) = R_A(\theta)$  and  $\theta^*$  rises, (2) the difference in slopes  $\delta_L - \delta_A$  rises, and/or (3)  $(\gamma_L - \gamma_A)$  rises.

**Case 2a:**  $\gamma_A - \gamma_L < 0$ , and  $\delta_L - \delta_A > 0$  . This case is represented by  $R_L$  and  $R'_A$  in [Figure 8b](#). The average readmission rate under laparoscopic assuming uniformly distributed patients with respect to  $\theta$  is represented in blue in [Figure 8b](#). The average among abdominal patients is the yellow area plus the green area. Now readmissions mean under laparoscopic rises relative to the mean under abdominal patients if (1) the number of patients between the  $\theta$  such that  $R_L(\theta) = R_A(\theta)$  and  $\theta^*$  declines (2) the relative slopes decline, and/or (3)  $R_L(\theta) - R_A(\theta)$  is lesser.

**Case 2b:**  $\gamma_A - \gamma_L < 0$ , and  $\delta_L - \delta_A < 0$  . In this case, the mean readmission rate under laparoscopic surgery is always greater than the rate under abdominal surgery,  $R''_A(\theta)$ . If  $\theta \sim Uniform$ , the blue area in [Figure 8b](#) is the average among laparoscopic patients and the green area is the average among abdominal patients.



(a) Case 1. Readmissions with respect to  $\theta$ , under each treatment alternative.

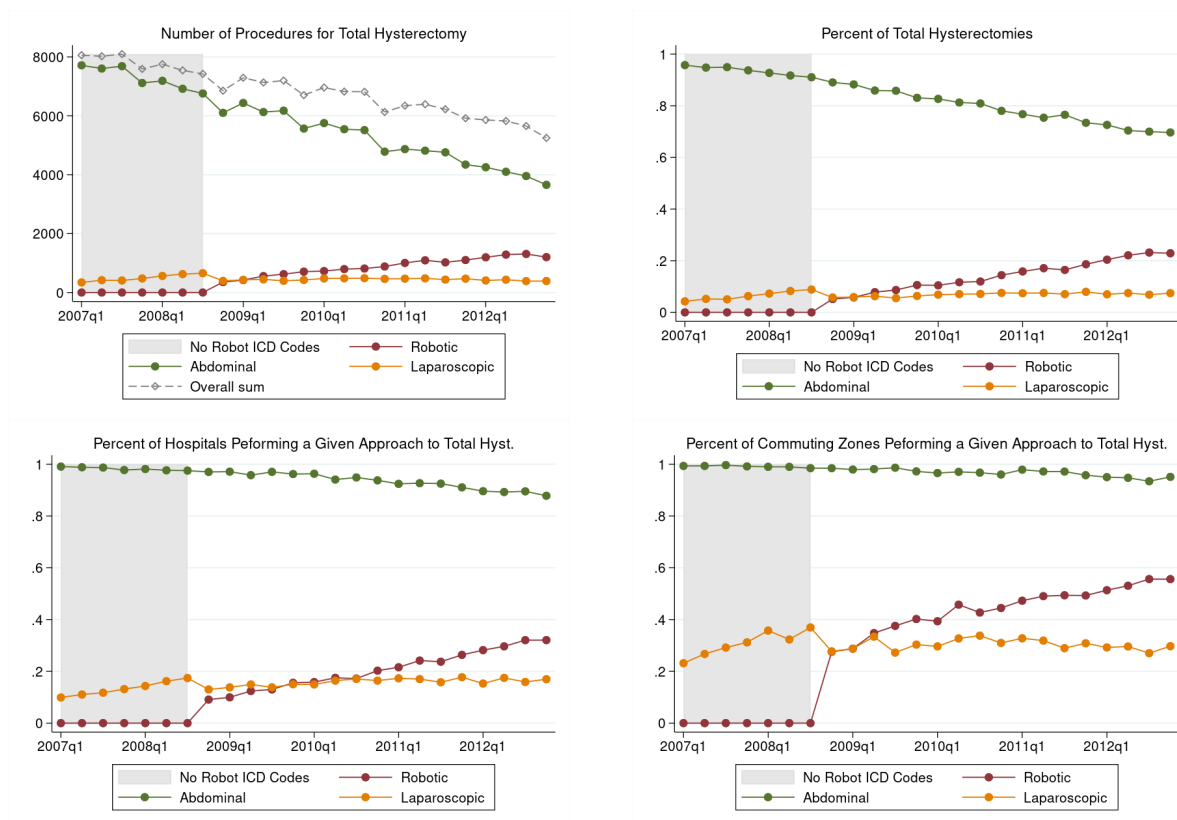


(b) Case 2a and Case 2b. Readmissions with respect to  $\theta$ , under laparoscopic treatment ( $R_L(\theta)$ ), under abdominal treatment in Case 2a ( $R'_A(\theta)$ ), and under abdominal treatment in Case 2b ( $R''_A(\theta)$ ).

## B Further Data Description

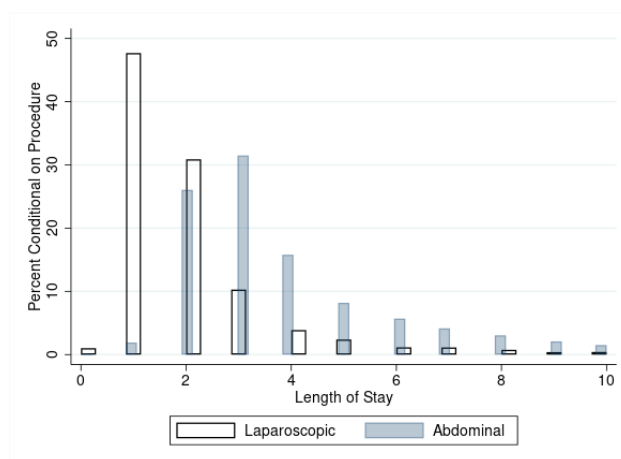
Figure 9 shows the trends in hysterectomy from 2007 to 2012. Note that the ICD-9 procedure code for robotically assisted procedure was introduced in the last quarter of 2008, and robotically assisted hysterectomies up to the point were coded as laparoscopic.

**Figure 9:** Trends in Types of Hysterectomies as Seen in Medicare Inpatient Claims, over Calendar Quarters



As of the mid to late 2000s, abdominal and minimally invasive surgery had been coexisting. Most procedures were performed with the oldest technology, abdominal surgery. As the robotic procedure has been used increasingly for hysterectomies, the abdominal procedure has been used decreasingly. The share of hysterectomies performed laparoscopically – the minimally invasive technology that is newer than abdominal surgery but older than robotic – has been roughly constant over time.

**Figure 10:** Distribution of Inpatient Length of Stay across Hysterectomies, by Procedure Type



## C Instrument Validity

This section presents evidence supporting the validity of the relative distance instrument, which is equal to the difference between a patient’s distance to her nearest hysterectomy-performing hospital that performs laparoscopic surgery and the distance to her nearest hysterectomy-performing hospital. Appendix [Table 7](#) presents evidence of the instrument’s exclusion from the outcome function by comparing the characteristics of patients whose relative distance is greater than the median to those whose relative distance is less than the median. Appendix [Table 8](#) presents the first stage results, showing instrument relevance. Appendix [Table 9](#) tests for instrument monotonicity by estimating the first stage in demographic- and diagnostic-based subsamples.

**Table 7:** Patient Characteristics in Top and Lower Half of Instrument's Distribution

	Lesser Relative Distance	Greater Relative Distance	Overall
Relative Distance to Lap. Hospital	0.0504 (0.188)	24.50 (28.70)	12.28 (23.69)
Lap % of Hyst.	0.0846 (0.278)	0.0484 (0.215)	0.0665 (0.249)
White	0.798 (0.402)	0.833 (0.373)	0.815 (0.388)
Black	0.153 (0.360)	0.123 (0.328)	0.138 (0.345)
Not Black or white	0.0492 (0.216)	0.0442 (0.206)	0.0467 (0.211)
HMO	0.0432 (0.203)	0.0371 (0.189)	0.0402 (0.196)
Charlson index	4.152 (2.618)	3.967 (2.654)	4.060 (2.637)
Diabetes	0.171 (0.376)	0.179 (0.383)	0.175 (0.380)
Malignant Neoplasm	0.486 (0.500)	0.451 (0.498)	0.469 (0.499)
Non-Malignant Neoplasm	0.317 (0.465)	0.326 (0.469)	0.321 (0.467)
BMI30+	0.0365 (0.188)	0.0256 (0.158)	0.0310 (0.173)
History of Cancer	0.0799 (0.271)	0.0766 (0.266)	0.0783 (0.269)
Uterine Fibroid	0.283 (0.451)	0.285 (0.451)	0.284 (0.451)
Endometriosis	0.103 (0.303)	0.118 (0.323)	0.111 (0.314)
Pelvic Organ Prolapse	0.0721 (0.259)	0.0796 (0.271)	0.0759 (0.265)
Female Genital Bleeding	0.118 (0.322)	0.135 (0.342)	0.127 (0.333)
Postmenopausal Bleeding	0.0985 (0.298)	0.101 (0.302)	0.0999 (0.300)
Other Ovarian Cyst	0.0807 (0.272)	0.0850 (0.279)	0.0828 (0.276)
Female Genital Pain	0.118 (0.322)	0.137 (0.344)	0.127 (0.333)
Pelvic peritoneal adhesions	0.0980 (0.297)	0.0998 (0.300)	0.0989 (0.299)

Characteristics among total hysterectomy patients. Lap = Laparoscopic. Hyst=Hysterectomies. HMO = Any months that year on Medicare Advantage (managed care). BMI30+ = Body mass index  $\geq 30$ , considered obese.



**Table 8:** First Stage Results: Linear Regression of Relative Hospital Distance Predicting Laparoscopic Choice

	(1)	(2)	(3)	(4)	(5)
Relative Distance	-0.000555*** (0.0000571)	-0.000580*** (0.0000575)	-0.000585*** (0.0000572)	-0.000414*** (0.0000532)	-0.000385*** (0.0000581)
Observations	54998	54998	54998	54978	48559
Laparoscopic Rate	0.0669	0.0669	0.0669	0.0670	0.0686
Instrument Mean	12.32	12.32	12.32	12.31	11.35
Demographic Controls		✓	✓	✓	✓
Clinical Controls			✓	✓	✓
Zip Code Controls				✓	✓
Hospital Controls					✓
Effective $F$	94.38	102.0	104.4	60.39	43.89

Standard errors in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ 

First stage with continuous instrumental variable for the estimation strategy to test the hypothesis about marginal patients by two-stage least squares. Across specifications, the instrumental variable is the difference between the patient's distance to her nearest hysterectomy-performing hospital with laparoscopic surgery and the distance to her nearest hysterectomy-performing hospital. The endogenous variable is an indicator for whether the hysterectomy was performed laparoscopically, rather than abdominally. Relative distance is measured in miles.

**Table 9:** Test for Monotonicity of Instrument

	Age < 65	Age ≥ 65	Age ≥ 75	Age < 75	64 < Age < 75	Age < 65 or Age > 74	White	Not White
Relative Distance	-0.000487*** (0.0000837)	-0.000332*** (0.0000696)	-0.000289*** (0.0000927)	-0.000416*** (0.0000606)	-0.000359*** (0.0000792)	-0.000405*** (0.0000672)	-0.000391*** (0.0000648)	-0.000286*** (0.0000966)
Observations	14751	33808	13703	34856	20105	28454	39713	8846

	Malignant Neoplasm	No Malignant Neoplasm	Fibroids	No Fibroids
Relative Distance	-0.000247*** (0.0000827)	-0.000482*** (0.0000664)	-0.000413*** (0.0000772)	-0.000372*** (0.0000694)
Observations	22698	25861	13744	34815

Standard errors in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

First stage regression run on subsets of the sample, where the dependent variable is whether a hysterectomy was performed laparoscopically and the independent variable is the instrumental variable, relative distance. Headers describe patient subsample. Relative distance is the difference between a patient's distance to her nearest hysterectomy-performing hospital with laparoscopic surgery and her distance to her nearest hysterectomy-performing hospital. First stage estimates are qualitatively the same and quantitatively similar across subsamples, suggesting that different types of patients respond to the instrument in the same way and that the instrument satisfies monotonicity.

## D Additional Two-Stage Least Squares Results

**Table 10:** Effect of Laparoscopic Procedure on the Probability of Any 90-day Readmission Accompanied by Urogenital Infection: 2SLS

	(1)	(2)	(3)	(4)	(5)
Laparoscopic	0.203*** (0.0550)	0.167*** (0.0516)	0.126** (0.0502)	0.247*** (0.0779)	0.195** (0.0923)
Observations	54998	54998	54998	54978	48559
Dependent Variable Mean	0.0325	0.0325	0.0325	0.0326	0.0325
Demographic Controls		✓	✓	✓	✓
Clinical Controls			✓	✓	✓
Zip Code Controls				✓	✓
Hospital Controls					✓
$F$	13.67	28.69	24.53	16.78	14.38
Adj. $R^2$	-0.0936	-0.0610	-0.0274	-0.122	-0.0764
First-Stage Effective $F$	94.38	102.0	104.4	60.39	43.89

Standard errors in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

Two-staged least squares estimates, using relative distance to hospital with laparoscopic surgery as instrument. Across specifications, the effective F statistic (due to [Montiel Olea and Pflueger \(2013\)](#) and [Kleibergen and Paap \(2006\)](#)) should be compared against either the two-stage least squares/limited information maximum likelihood critical value for 5% bias, which is 37.418, or for 10% bias, which is 23.109. Demographic controls: whether the patient is Black, a race other than white or Black, under 65 years of age, or over 74 years of age. Clinical controls: the Charlson comorbidity index and indicators for whether the patient had diabetes, malignant neoplasm, non-malignant neoplasm, body mass index of 30 or over (considered obese), history of cancer indicated on the hysterectomy claim, uterine fibroids, endometriosis, pelvic organ prolapse, female genital bleeding, post-menopausal bleeding, an ovarian cyst, female genital pain, or peripheral adhesions. Zip code controls of the patient's residence: white percent of residents, the college-educated percent of residents, the percent of residents with public assistance (including cash or nutritional assistance), the median household income, and the percent of residents on Medicaid. Hospital controls: number of hysterectomies the hospital performed that year, a quality measure on the appropriate use of antibiotics, a quality measure on the prevention of blood clots in heart patients, and the overall Consumer Assessment of Healthcare Providers & Systems (CAHPS) score.

## E Additional Results from Marginal Treatment Effect Estimations

### E.0.1 Results Using Local Instrumental Variable Method

This subsection provides support for the model’s predictions for marginal patients using the local instrumental variable method. [Figure 11](#) graphically presents the estimates of marginal treatment effects with respect to percentiles of unobserved resistance to laparoscopic hysterectomy, under four different parametric approaches to modeling the outcomes as functions of unobserved heterogeneity and four different semiparametric approaches. Subfigure (a) summarizes the estimates across all model specifications. Figures (b) through (i) show the estimates one at a time from each model, as well as 95 percent confidence intervals. Standard errors are analytically derived for parametric models and bootstrapped for semiparametric models. Effects are statistically significant across most percentiles in each model result. The local average treatment effect estimate from [Table 4](#), Column 4,  $-0.54$ , is near the middle of marginal treatment effects estimated over the supported range of percentiles of resistance.

[Figure 12](#) presents analogous results of marginal treatment effects on the chance of an all-cause 90-day readmission. Subfigure (a) summarizes results across models and shows that estimated marginal treatment effects are positive and upward sloping as functions of unobserved resistance to laparoscopic surgery, across model specifications. Point estimates from parametric models, presents with confidence intervals in subfigures (b) through (i), are not statistically significant at the 95 percent level at any levels of unobserved resistance, although for some percentiles around 0.05 and 0.1, for which there is substantial common support, much of the probability mass of the point estimates are positive. The local average treatment effect estimate from [Table 5](#), Column 4,  $0.36$ , is near the middle of marginal treatment effects estimated over the supported range of percentiles of resistance.

The estimates from local instrumental variable estimation of marginal treatment effects on length of stay and readmission rate are supportive of the model’s prediction of a tradeoff among marginal patients between the two adverse clinical outcomes. This is not surprising, since the local average treatment effects, estimated above, are known to be weighted combinations of marginal treatment effects across the support of the instrumental variable.

### E.1 Results Using Separate Method

This subsection presents estimates of marginal treatment effects on length of stay and readmission risk from the separate estimation method, presented analogously to the results from local instrumental variable

estimation. The results largely resemble the results from the local instrumental variable approach. [Figure 13](#) shows that across model specifications, marginal treatment effects on having a length of stay of two or more days are estimated to be negative and, as a function of unobserved resistance, is estimated to be downward sloping.

[Figure 14](#) shows that the estimates of effects on any readmission from the separate method, like in the local instrumental variable approach, are positive across most of the support, but not statistically significant at the 95 percent confidence level. One difference is that estimates from the separate method suggest that the marginal treatment effects as a function of unobserved resistance is upward sloping, whereas the local instrumental variables method suggested it is downward sloping. Over the support, the separate method estimates that the marginal treatment effect varies from about 0.5 to zero. The two-stage least squares estimate of the local average treatment effect on readmission risk is 0.361, controlling for demographic, clinical, and Zip code-level controls, and it is 0.173 when additionally controlling for hospital characteristics. These estimates of the local effect fall within the range of estimated marginal effects.

## E.2 Marginal Treatment Effect Weights

The local average treatment effect is a weighted combination of the marginal treatment effects across all percentiles of unobserved resistance. [Figure 15](#) plots the weights, estimated from data, that relate the marginal treatment effect at a particular level of unobserved resistance to the local average treatment effect.

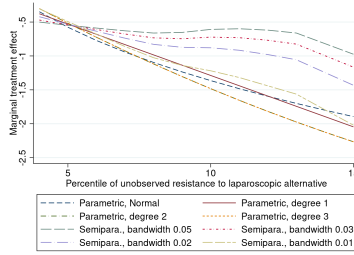
Recall from [Heckman and Vytlacil \(1999, 2005\)](#) and [Heckman, Urzua and Vytlacil \(2006\)](#) that

$$LATE_Y(p_0, p_1) = \int_{p_0}^{p_1} MTE_Y(p) \varphi_{IV}^Z(u_{D_L}) dp \quad (59)$$

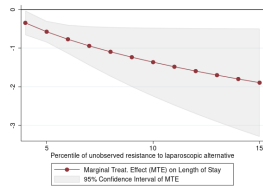
where the weights relating the MTEs to the LATE are:

$$\varphi_{IV}^Z(u_D) = \frac{\mathbb{E}[Z - \mathbb{E}[Z] \mid P(Z) > u_D] \Pr(P(Z) > u_D)}{\text{Cov}(Z, D)}$$

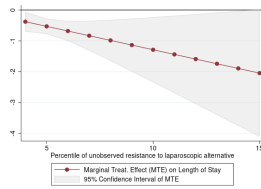
Certain observations are weighted more heavily if their treatment covaries with particular ranges of the instrument more. The weights integrate to one, can be negative if the instrument does not satisfy monotonicity, and can be consistently estimated from the sample.



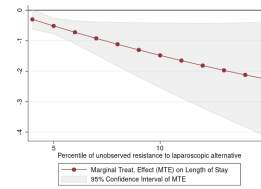
(a) All estimates of effect on readmission, from separate method. Summarizes estimates in plots (b) through (g).



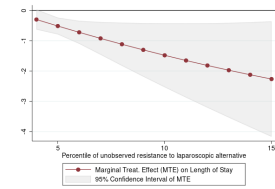
(b) Parametric: Normal.



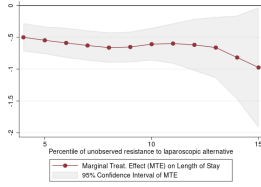
(c) Parametric: first-degree polynomial.



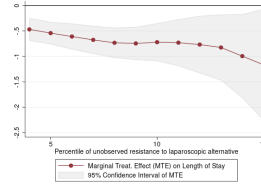
(d) Parametric: second-degree polynomial.



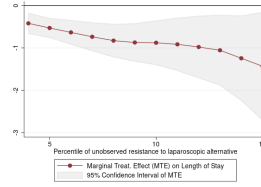
(e) Semiparametric: third-degree polynomial.



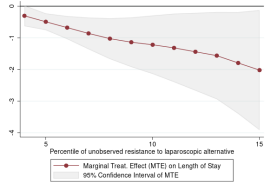
(f) Semiparametric: bandwidth 0.05.



(g) Semiparametric: bandwidth 0.03.

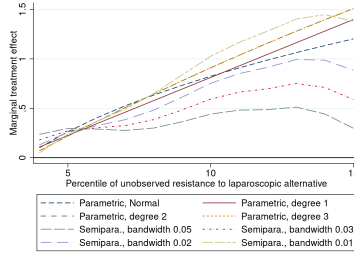


(h) Semiparametric: bandwidth 0.02.

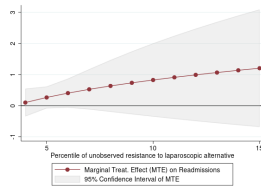


(i) Semiparametric: bandwidth 0.01.

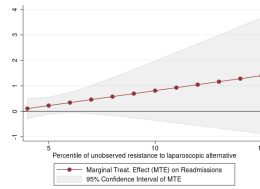
**Figure 11: Local Instrumental Variable Method: Length of Stay.** Estimates of marginal treatment effects of laparoscopic surgery, as opposed to abdominal surgery, on the probability of the length of stay being two or more days, using the separate approach. The horizontal axis in each plot is  $U_D$ , the case's percentile on the distribution of unobserved “resistance” to or “cost” of the laparoscopic choice. Gray bands are 95% confidence intervals. Unobserved heterogeneity, modeled as a function of the propensity score,  $p$ , is alternatively modeled parametrically (either Normal or as a polynomial of  $p$ ) or semiparametrically, using the Epanechnikov kernel with alternative bandwidths. Standard errors are bootstrapped with 100 repetitions. Subfigure (a) summarizes the point estimates in plots (b) through (h).



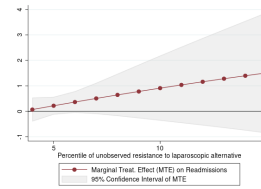
(a) All estimates of effect on readmission, from separate method. Summarizes estimates in plots (b) through (g).



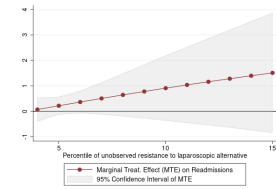
(b) Parametric: Normal.



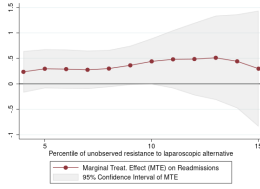
(c) Parametric: first-degree polynomial.



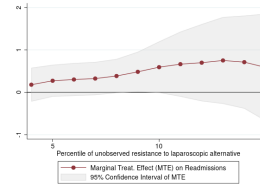
(d) Parametric: second-degree polynomial.



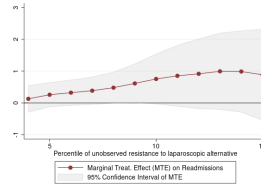
(e) Semiparametric: third-degree polynomial.



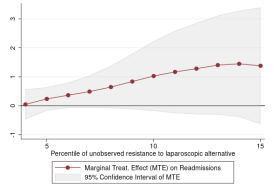
(f) Semiparametric: bandwidth 0.05.



(g) Semiparametric: bandwidth 0.03.

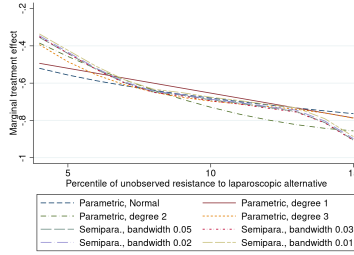


(h) Semiparametric: bandwidth 0.02.

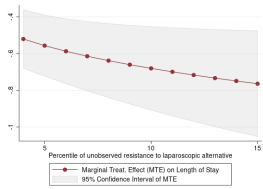


(i) Semiparametric: bandwidth 0.01.

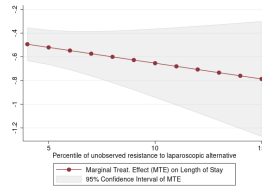
**Figure 12: Local Instrumental Variable Method: Readmissions.** Estimates of marginal treatment effects of laparoscopic surgery, as opposed to abdominal surgery, on the probability of an all-cause 90-day readmission, using the local instrumental variable approach. The horizontal axis in each plot is  $U_D$ , the case's percentile on the distribution of unobserved “resistance” to or “cost” of the laparoscopic choice. Gray bands are 95% confidence intervals. Unobserved heterogeneity, modeled as a function of the propensity score,  $p$ , is alternatively modeled parametrically (either Normal or as a polynomial of  $p$ ) or semiparametrically, using the Epanechnikov kernel with alternative bandwidths. Standard errors are bootstrapped with 100 repetitions. Subfigure (a) summarizes the point estimates in plots (b) through (h).



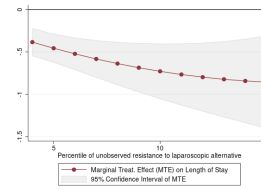
(a) All estimates of effect on readmission, from separate method. Summarizes estimates in plots (b) through (g).



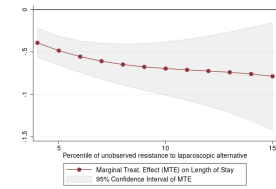
(b) Parametric: Normal.



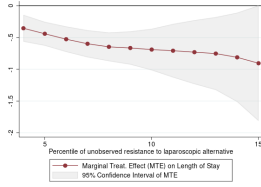
(c) Parametric: first-degree polynomial.



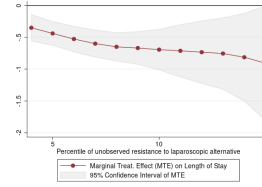
(d) Parametric: second-degree polynomial.



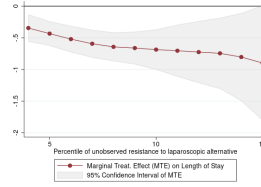
(e) Semiparametric: third-degree polynomial.



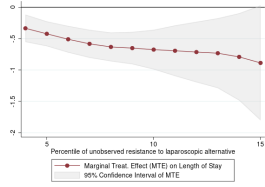
(f) Semiparametric: bandwidth 0.05.



(g) Semiparametric: bandwidth 0.03.



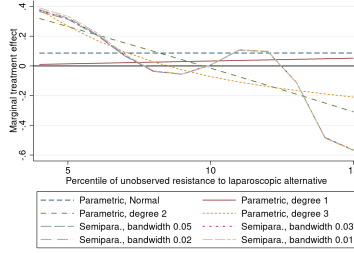
(h) Semiparametric: bandwidth 0.02.



(i) Semiparametric: bandwidth 0.01.

**Figure 13: Separate Method: Length of Stay.** Estimates of marginal treatment effects of laparoscopic surgery, as opposed to abdominal surgery, on the probability of the length of stay being two or more days, using the separate approach. The horizontal axis in each plot is  $U_D$ , the case's percentile on the distribution of unobserved “resistance” to or “cost” of the laparoscopic choice. Gray bands are 95% confidence intervals. Unobserved heterogeneity, modeled as a function of the propensity score,  $p$ , is alternatively modeled parametrically (either Normal or as a polynomial of  $p$ ) or semiparametrically, using the Epanechnikov kernel with alternative bandwidths. Standard errors are bootstrapped with 100 repetitions. Subfigure (a) summarizes the point estimates in plots (b) through (f).

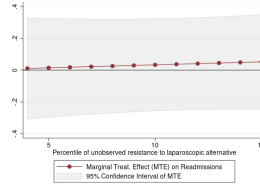




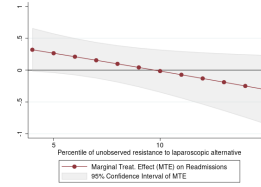
(a) All estimates of effect on readmission, from separate method. Summarizes estimates in plots (b) through (g).



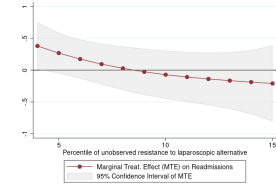
(b) Parametric: Normal.



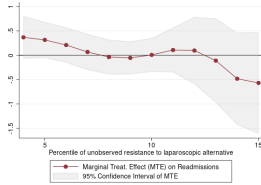
(c) Parametric: first-degree polynomial.



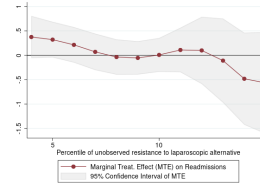
(d) Parametric: second-degree polynomial.



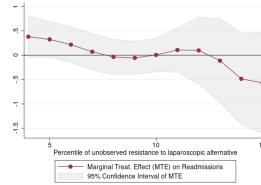
(e) Semiparametric: third-degree polynomial.



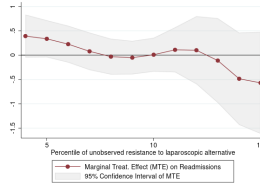
(f) Semiparametric: bandwidth 0.05.



(g) Semiparametric: bandwidth 0.03.



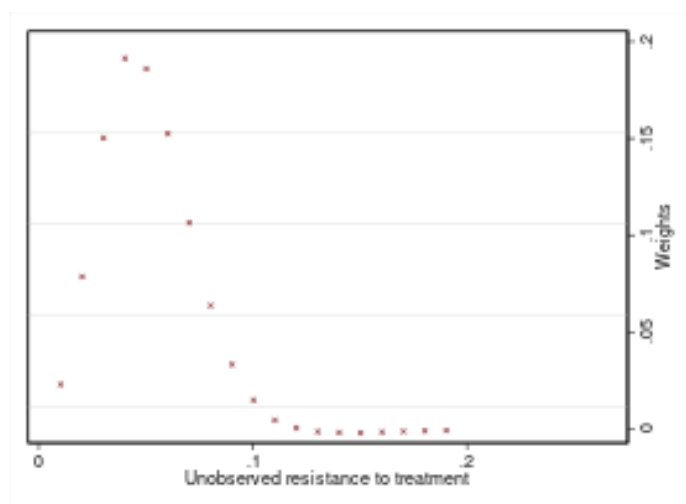
(h) Semiparametric: bandwidth 0.02.



(i) Semiparametric: bandwidth 0.01.

**Figure 14: Separate Method: Readmission.** Estimates of marginal treatment effects of laparoscopic surgery, as opposed to abdominal surgery, on the probability of an all-cause 90-day readmission, using the separate approach. The horizontal axis in each plot is  $U_D$ , the case's percentile on the distribution of unobserved “resistance” to or “cost” of the laparoscopic choice. Gray bands are 95% confidence intervals. Unobserved heterogeneity, modeled as a function of the propensity score,  $p$ , is alternatively modeled parametrically (either Normal or as a polynomial of  $p$ ) or semiparametrically, using the Epanechnikov kernel with alternative bandwidths. Standard errors for parametric models are calculated analytically, while standard errors for semiparametric models are bootstrapped with 100 replications. Subfigure (a) summarizes the point estimates in plots (b) through (g).

**Figure 15:** Weights Relating the Marginal Treatment Effects to the Local Average Treatment Effects



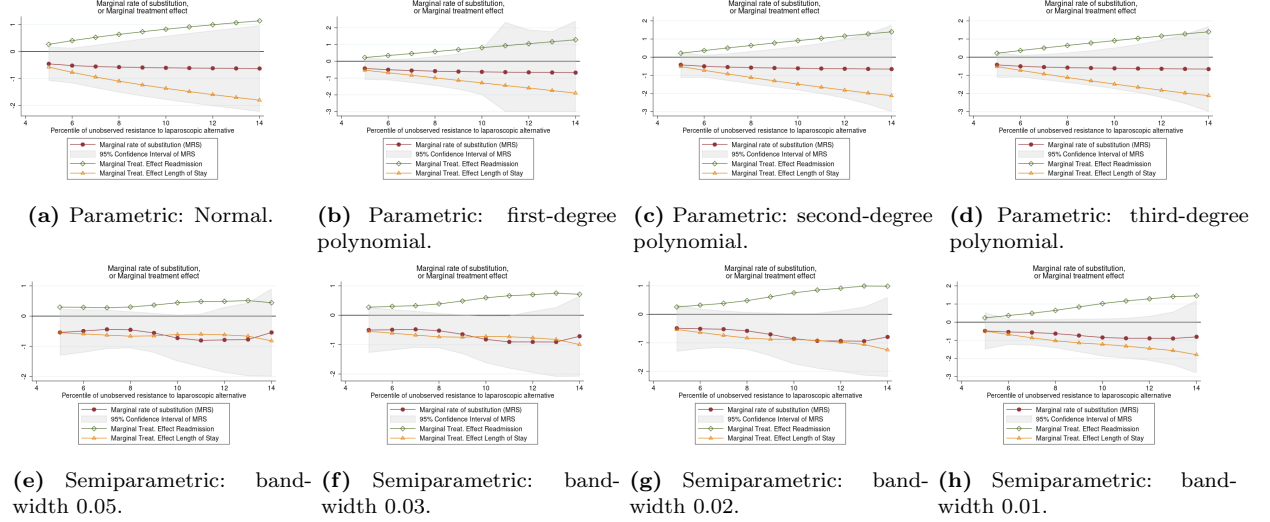
The horizontal axis in each plot is  $U_D$ , the case's percentile on the distribution of unobserved “resistance” to or “cost” of the laparoscopic choice. The Xs indicate the weight that relates the marginal treatment effect at that percentile to the local average treatment effect.

## F Full Marginal Rate of Substitution Estimates

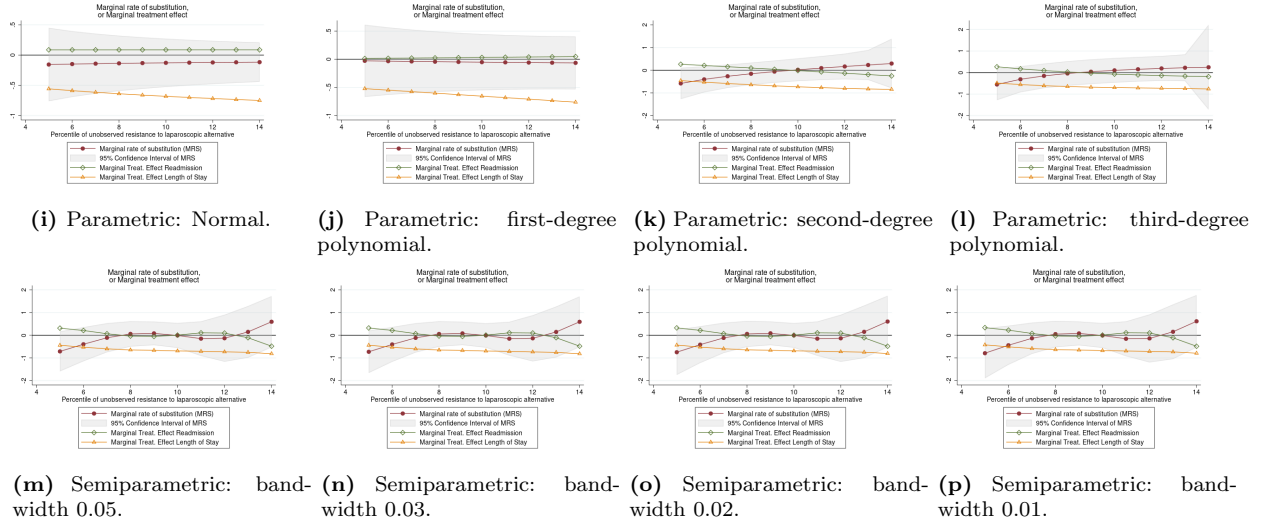
Figure 16 presents the estimates of the marginal rates of substitution, and their respective confidence intervals, calculated from the marginal treatment effects on length of stay and on readmission, which are also plotted alongside.

**Figure 16:** Estimates of Marginal Rate of Substitution, Their Confidence Intervals, and Marginal Treatment Effects

### Estimates from Local Instrumental Variable Method



### Estimates from Separate Method



Estimates of marginal rate of substitution (MRS) and, in gray bands, their 95% confidence intervals, as well as the marginal treatment effects of the separate method from which they are calculated. The horizontal axis in each plot is  $U_D$ , the case's percentile on the distribution of unobserved "resistance" to or "cost" of the laparoscopic choice. Unobserved heterogeneity, modeled as a function of the propensity score,  $p$ , is alternatively modeled parametrically (either Normal or as a polynomial of  $p$ ) or semiparametrically, using the Epanechnikov kernel with alternative bandwidths. Standard errors for parametric models are calculated analytically, while standard errors for semiparametric models are bootstrapped with 100 repetitions. In Panel (b), the plotted lower confidence bounds for the MRS at  $U_D = 11, \dots, 14$  are truncated. They reach a minimum of -5.

## G Robustness Checks

**Table 11:** Effect of Laparoscopic Procedure on the Probability of Length of Stay is 3 or More Days: 2SLS

	(1)	(2)	(3)	(4)	(5)
Laparoscopic	0.616** (0.258)	0.198 (0.223)	-0.175 (0.208)	-0.570** (0.285)	-0.556 (0.345)
Observations	54998	54998	54998	54978	48559
Dependent Variable Mean	0.707	0.707	0.707	0.707	0.707
Demographic Controls		✓	✓	✓	✓
Clinical Controls			✓	✓	✓
Zip Code Controls				✓	✓
Hospital Controls					✓
$F$	5.684	300.0	183.7	162.3	135.3
Adj. $R^2$	-0.310	-0.0264	0.155	0.196	0.203
First-Stage Effective $F$	94.38	102.0	104.4	60.39	43.89

Standard errors in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

Two-staged least squares estimates, using relative distance to hospital with laparoscopic surgery as instrument. Across specifications, the effective F statistic (due to [Montiel Olea and Pflueger \(2013\)](#) and [Kleibergen and Paap \(2006\)](#)) should be compared against either the two-stage least squares/limited information maximum likelihood critical value for 5% bias, which is 37.418, or for 10% bias, which is 23.109. Demographic controls: whether the patient is Black, a race other than white or Black, under 65 years of age, or over 74 years of age. Clinical controls: the Charlson comorbidity index and indicators for whether the patient had diabetes, malignant neoplasm, non-malignant neoplasm, body mass index of 30 or over (considered obese), history of cancer indicated on the hysterectomy claim, uterine fibroids, endometriosis, pelvic organ prolapse, female genital bleeding, post-menopausal bleeding, an ovarian cyst, female genital pain, or peripheral adhesions. Zip code controls of the patient's residence: white percent of residents, the college-educated percent of residents, the percent of residents with public assistance (including cash or nutritional assistance), the median household income, and the percent of residents on Medicaid. Hospital controls: number of hysterectomies the hospital performed that year, a quality measure on the appropriate use of antibiotics, a quality measure on the prevention of blood clots in heart patients, and the overall Consumer Assessment of Healthcare Providers & Systems (CAHPS) score.