The Timing of New Technology Adoption: The Case of MRI *

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Abstract

This paper studies the adoption of nuclear magnetic resonance imaging (MRI) by US hospitals. I consider a timing game of new technology adoption. The dynamic game allows me to take both timing decisions and strategic interaction into account. The model can be solved using standard dynamic programming techniques. Using a panel data set of US hospitals, cross sectional variation in adoption times, market structure and demand is exploited to recover the profit and cost parameters of the timing game. In counterfactual experiments I decompose the cost of competition into a business stealing and a preemption effect. I find substantial changes in adoption times and industry payoffs due to competition. These changes are mostly due to a business stealing effect. Preemption accounts for a significant but small share of this change.

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1 Introduction

While technological progress is generally viewed as the fundamental driving force of economic performance, the existence of a new technology alone is not sufficient for economic progress. It is the diffusion of the new technology among potential users that determines how it affects the economic environment. We would like to understand what determines the timing of new technology adoption.

This paper focuses on how varying degrees of competition affect the decision to adopt a new technology and how technology adoption in turn affects payoffs. I develop and estimate an empirical model of new technology adoption by hospitals in the United States. I consider a timing game of new technology adoption. The dynamic game allows me to take both the timing decision and strategic interaction into account.

The empirical model developed here draws on a large theoretical literature that studies the strategic timing of technology adoption.[1] Every period, firms decide whether or not to adopt the new technology. I consider subgame perfect equilibria in adoption times and thus require that each firm's decision be optimal at every point in time. A firm's decision depends on the cost of the new technology, the direct effect of adoption on its current and future payoffs and the effect on rivals' adoption times. Two sources of inefficiency can arise in this model: First, there is business stealing: Firms gain from new technology adoption in part at expense of their rivals. Second, a preemption motive may determine the equilbrium adoption time: A firm adopts early to discourage its rivals from adopting and secures the rents from adoption. This paper builds a framework to quantify the relative importance of business stealing and preemption in technology adoption.

In such a model, multiple equilibria may arise. This poses a problem for the estimation, because a cross-section of markets is needed to identify the parameters of interest and different equilibria may be played in different markets. In recent work Einav (2003a) and Sweeting (2004) develop methods to estimate the parameters of games of timing with multiple equilibria.[2] These papers consider models where players make their timing decision only

[1] See Hoppe (2002) for a survey of these models.

[2] Einav (2003a) studies the timing of product introduction in the context of movie release dates. Movie distributors announce the release dates in an exogenously fixed and predetermined order. Each player moves

once. In many applications it is not plausible to assume that firms precommit to an adoption date several years in the future. Hence, I study a model where firms can decide every period whether to adopt the new technology. I assume that firms move sequentially in every period. The assumed order of moves is justified by showing that it produces the same equilibrium order of adoptions as the simultaneous move game when time periods are sufficiently short. With this sequential structure of moves there is a unique subgame perfect equilibrium in this game. I can solve for the subgame-perfect equilibrium using a simple recursive algorithm. I construct a method of moments estimator based on the equilibrium adoption times.

Existing empirical studies of new technology adoption consider competitive (Griliches (1957)) and monopolistic settings (Rose and Joskow (1990)), but also environments where strategic interaction might play a role (e.g. Karshenas and Stoneman (1993), Levin, Levin and Meisel (1987, 1992), Baker (1999), and Baker and Phibbs (2000)). A common approach in this literature is to include rivals' adoptions or the number of rivals as an explanatory variable in the hazard function.[3] The interpretation of the estimated coefficients on rivals' actions in light of the existing theoretical models is complicated by the potential endogeneity of rivals' adoption times: A firm's decision regarding when to adopt depends on its belief about rivals' adoption times and their effect on its own profits. The endogeneity of the adoption decision has been addressed in static frameworks either by using instrumental variable techniques (Gowrisankaran and Stavins (2002)), or by explicitly modelling technology adoption as a static game (see Dranove, Shanley and Simon (1992), and Chernew, Gowrisankaran and Fendrick (2001)). The drawback of these approaches is that the time dimension of the adoption decision has to be ignored.

The current paper accounts for both the endogeneity and the dynamic character of the

only once. The equilibrium in this sequential game is unique. Using measures of seasonal demand obtained in Einav (2003b), estimation results from the timing model suggest that release dates are too clustered. In Sweeting (2004) a coordination game is studied, in which radio stations simultaneously decide when to air their radio commercials. He shows that there are benefits to coordination. The presence of multiple equilibria in this coordination game is employed to identify and measure this incentive.

[3]Exceptions are Vogt (1999) and Genesove (1999) who carefully study the effect of firm heterogeneity and rival adoption on the adoption probabilities in duopoly markets and compare them to predictions from the theoretical literature. Contrary to these papers I am not restricting the analysis to duopoly markets.

adoption decision. I estimate the return and cost parameters of a general timing game that builds on the theoretical literature on technology adoption. Knowledge of these return and cost parameters is necessary to perform counterfactual experiments that quantify the relative significance of strategic interaction in technology adoption.

I study hospital competition in the context of magnetic resonance imaging (MRI) adoption. MRI is a diagnostic tool for producing high resolution images of body tissues. It first became commercially available in the early 1980s and diffused slowly during the subsequent two decades. The cost of new medical technologies has repeatedly been blamed for the increase in health care expenditures. Competition among hospitals has been depicted as wasteful and leading to a 'medical arms race.' MRI is a typical example of an expensive new medical technology. A high fixed asset investment of about US$ 2 million is required for a new imager.

For the empirical analysis a panel data set containing demographic and income variables, as well as the adoption times of hospitals for a large number of markets in the United States has been constructed by combining information from the American Hospital Association's annual survey database and the U.S. Census. I consider markets with a small number of hospitals, where I expect it to be easier to isolate strategic interaction empirically than in larger markets.

The adoption of MRI will affect revenues and cost of hospitals but it is a small investment decision relative to entering or exiting a market. Consequently, the number of hospitals and hospital characteristics are viewed as exogenous to the adoption decision. Using information on the timing of MRI adoption within markets as well as varying degrees of competition and demand across markets I can separate effects of competition, demand and costs on the timing decision.

In equilibrium, hospitals' adoption times are determined either by their stand-alone incentive, the marginal benefit of adopting, or the preemption incentive, the incentive to adopt before your rival in order to delay her adoption. Thus, equilibrium adoption times are not only informative about the marginal benefit of adopting, but also about the relative benefit of being the follower versus the leader. This enables me to identify the effect of rivals' adoption on the payoffs of adopters and non-adopters separetely. I find that returns to adoption decline substantially with the number of adopters. The effect of rival adoption on non-adopters' payoffs is significant but substantially smaller.

The model allows for heterogeneity in hospital profits. I find that organizational structure and hospital size influence the adoption decision. Nonprofit and for-profit hospitals are more likely to adopt the new technology than community hospitals. Large hospitals benefit more from MRI adoption. Cost function estimates indicate that the real cost of adopting MRI declines by three percent per year

I perform two counterfactual experiments that quantify to what extent competition causes inefficiencies from the hospital industry's perspective. In the first experiment, a regulator chooses adoption times to maximize industry profits. Thus the regulator takes into account both sources of inefficiency, business stealing and preemption. This regime delays hospitals' adoption times by as much as four years and increases the industry profits from adoption by as much as 5.5 percent. In the second experiment I examine the role of preemption alone by comparing the Nash equilibrium adoption times to the subgame perfect equilibrium outcome.[4] In a Nash equilibrium firms precommit to their adoption times as in Reinganum (1982), which removes the incentive to preempt in order to delay the rival's adoption time. I find that preemption accounts for about one sixth of the overall loss of industry profits arising from strategic adoption timing.

The remainder of the paper is structured as follows. The next section describes the MRI technology and its significance for the US hospital industry, summarizes the construction of the data set, and presents evidence of the diffusion of MRI by between 1986 and 1993. Section 3 introduces a discrete time model of technology adoption and discusses the equilibrium properties. Section 4 describes the estimation approach and presents the estimates of the model presented in Section 3. In Section 5 a counterfactual experiment is conducted under which a regulator chooses adoption times to maximize intertemporal industry profits. Section 6 concludes.

[4]The impact of preemption on industry profits has been emphasized in the theoretical literature (e.g. Fudenberg and Tirole (1985) and Riordan (1992)).

2 The diffusion of MRI

In this section I describe magnetic resonance imaging, the construction of the data set, and present the key features of the data.

2.1 Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is a diagnostic tool for producing high resolution images of body tissues. It became commercially available in the early 1980s, when eight companies had already completed prototypes. MRI is superior to most other imaging techniques in providing images of the brain, heart, liver, kidneys, spleen, pancreas, breast, and other organs. The adoption of MRI by US hospitals occurred slow relative to the computer tomography scanner (CT scanner). One reason is a very high capital cost, about 10 times that of a CT scanner; the cost of the equipment ranging from \$2 million to \$2.6 million, and the installation cost ranging from \$0.6 million. to \$1.3 million in 1985 (Steinberg and Evens (1988)). The cost of equipment declined over time at a rate of 4.5% in real terms (Bell (1996)). A crucial reason for adopting MRI was the Health Care Finance Administration's 1985 approval of coverage for scans performed on Medicare patients.[5] Hospital managers may also have been of the prestige effect of an imager. Muroff (1992) states for example that there is "economic impact of having a 'state-of-the art,' multipurpose MRI unit that might be necessary to win referrals in a highly competitive environment. [...] Quantifying these benefits is difficult." A survey of hospital executives carried out by the American Hospital Association in 1987 shows that competition was the second most important reason for purchasing MRI, the number one reason being 'improving patient care.'

2.2 Data Description

I use two sources of data for the empirical analysis. First, I use adoption data derived from the American Hospital Association's (AHA) annual survey database. The AHA surveys all hospitals operating in the United States every year. I have constructed a dataset of non-

[5] The coverage was limited to scans performed with imagers that had won the Food and Drug Administration's pre-market approval. In 1985, five firms supplied models with pre-market approval.

federal general medical and surgical hospitals. That means I exclude rehabilitation hospitals, childrens hospitals and psychiatric clinics. I also exclude federal hospitals such as Army or Veterans Administration hospitals. The AHA survey has been used previously to analyze the diffusion of MRI. Baker (2001) studies the impact of HMO market share on MRI diffusion in a hazard framework. There, the emphasis is on individual hospitals in larger markets, whereas I focus on strategic interaction among hospitals in small markets. I have however adopted Bakers's definition of adoption: I record a hospital as having adopted MRI in a given year if it responds in the survey that it has a hospital based nuclear magnetic resonance imaging facility. The survey also includes hospital specific information such as a control code (like non-profit versus for profit status), the number of beds, whether it belongs to the Council of Teaching Hospitals, or has a residency program. This information is available for eight years from 1986 to 1993.

As common in the health literature (Baker (2001), Baker and Phibbs (2000)), I define a market as a so-called Health Care Service Area (HCSA). HCSA's are groups of counties constructed to approximate markets for health care services based on Medicare patient flow data (Makuc et al. (1991)). Bell (2001) shows that MRI usage by Medicare patients relative to other patient groups is surprisingly small compared to other medical technologies. This leads me to assume that this market definition is exogenous to the presence of MRI. There are 802 HCSA's in the entire United States. The emphasis of this paper is on strategic interaction in technology adoption. Thus I restrict the analysis to 'small' markets with a constant number of four hospitals or less over time. While strategic interaction may also be present in markets with more hospitals, this interaction may be restricted to a small set of hospitals within those markets. The restriction to four hospitals or less leaves 306 HCSA's. I observe 58 monopoly markets, 91 duopoly markets, 88 markets with three firms and 69 markets with four firms. In total there are 780 hospitals, 322 of which are community hospitals, 407 are nonprofit hospitals and 51 are for-profit hospitals.

The second data source I use are the Area Resource Files (ARF), which provide county-level information on demographic and economic variables derived from US census. I aggregate population and per capita income to the HCSA level, and merge the information with the hospital data derived from the American Hospital Association's annual survey.

2.3 Stylized Facts

In Figure 1, I plot the fraction of markets with a given number of hospitals with at least one MRI over time. Starting in 1988 this fraction is always larger the larger the number of hospitals in a market. Ignoring market characteristics, this suggests that incentives to adopt first are larger in markets with more hospitals. Only a slow increase in the number of markets having adopted at least one MRI can be observed over time. The average adoption rate at the end of my sample is about 25 percent. Diffusion is slow, suggesting that the new technology is not immediately profitable for most hospitals.

To examine the relation between the number of hospitals and adoption decisions more detail, Table 1 cross tabulates the number of adoptions by 1993 with the number of hospitals in a HCSA. In brackets are the percentages of markets with the corresponding number of adopters. I observe only a small number markets with more than one hospital having adopted. The probability of having at least one MRI is increasing in the number of firms. The probability of a second adoption to occur is considerably smaller. In particular in duopoly markets, the conditional probability of a second adoption is lower than the probability of adoption by a monopolist. This suggests that there is an advantage to adopting first in an oligopoly market, but that marginal benefits to adopt decline once a competing hospital has adopted.

Table 2 tabulates the covariates that are used as proxies for demand against the numbers of hospital. On average, population is larger in markets with more hospitals. Mean per capita income appears to be unrelated with the number of hospitals.

3 A model of technology adoption

The features of MRI can be summarized as follows. An originally expensive new technology with costs falling over time. It slowly diffused over the past two decades. The adoption generates a new source of revenue, and there is a strategic component to adopting the new technology. In this section I present a model that resembles the features of MRI. First, I introduce a model of new technology adoption timing. I then discuss the equilibrium properties of this model.

3.1 Model

The aim is to build a model that is capable of reproducing the patterns of MRI diffusion in small hospital markets. The model assumptions are similar to those found in the existing theoretical literature. Existing research either restricts the attention to duopoly markets (Fudenberg and Tirole (1985), Reinganum (1981a), Riordan (1992)), or requires payoffs to be symmetric (Reinganum (1981b)). The emphasis of the current paper is on variation in market structure and the timing of adoption. Thus I build a model that allows for firm heterogeneity and an arbitrary number of firms. Because the definition of strategies and histories involves various technical difficulties in continuous time[6] and my data are discrete, I introduce a game in discrete time which is more suitable for empirical analysis. There are I firms denoted by $i = 1, ..., I$. Firms can choose to adopt at time $t = 1, 2, ..., \infty$.

I define firm i's *history of actions,* h_t^i, to be a t vector containing zeros until firm i has adopted, and ones from then on. Let H_t be the set of all possible action histories at time t. If firm i has not moved at any $\tau < t$, i.e. $h_t^i = (0, 0, ..., 0)$, then its *action set* at time t is

$$A_{h_t}^i = \{\text{do not adopt}, \text{adopt}\} = \{0, 1\}.$$

I assume that firms hold on to the technology indefinitely once they have adopted. This implies that the action set is weakly increasing in time. Let a_t^i denotes firm i's action at time t and $\mathbf{a}_t$ is the vector of actions at time t. Let n_t be the number of adopters in period t :

$$n_t = n(\mathbf{a}_t) = \sum_{i=1}^{I} \mathbf{1}_{\{a_t^i = 1\}}$$

A firm receives $\pi_0^i(n(\mathbf{a}_t))$ per period before adoption and $\pi_1^i(n(\mathbf{a}_t))$ therafter. Let t^i be firm $i's$ adoption time. At the time of adoption it incurs a sunk cost of $C(t^i)$. Firms discount future returns with discount factor β. Hence, a firm's discounted intertemporal profits are

$$\Pi^i = \sum_{t=1}^{t^i - 1} \beta^t \cdot \pi_0^i(n(\mathbf{a}_t)) + \sum_{t=t^i}^{\infty} \beta^t \cdot \pi_1^i(n(\mathbf{a}_t)) - \beta^{t^i} \cdot C(t^i)$$

Firms choose a strategy to maximize their discounted profits Π^i.

[6] See for example Simon and Stinchcombe (1989).

An adoption strategy for firm i is a function mapping the history to an element of the action set:

$$s_t^i : h_t \rightarrow A_t^i(h_t) \quad \forall h_t \in H_t$$

Let $\mathbf{s_u^i} = \{s_t^i\}_{t=u}^{\infty}$ be the sequence of adoption strategies starting at time $\mathbf{u}$. $\mathbf{s_u^{-i}}$ denotes the sequence of strategies by players other than i. A *subgame perfect equilibrium* is an I-tuple of adoption strategies $\{\mathbf{s^1}, \mathbf{s^2}, .., \mathbf{s^i}, .., \mathbf{s^I}\}$ that constitutes a Nash equilibrium in every subgame.

I now introduce a set of assumptions regarding the payoff and cost functions.

A1: (monotonicity) $\pi_a^i(n-1) \geq \pi_a^i(n)$ *for* $a = \{0, 1\}$ *and* $1 \leq n, i \leq I$,

A2: (positive returns) $\pi_1^i(n) \geq \pi_0^i(n-1)$; $\forall\ 1 \leq i, n \leq I$

A3: (decreasing returns:) $\pi_1^i(n-1) - \pi_0^i(n-2) \geq \pi_1^i(n) - \pi_0^i(n-1)$; $\forall\ 1 \leq i \leq I$, $\forall\ 2 \leq n \leq I$

A4: (profitability order) $\pi_1^i(n) - \pi_0^i(n-1) > \pi_1^j(n) - \pi_0^j(n-1)$ *if and only if*
$\pi_1^i(m) - \pi_0^i(m-1) > \pi_1^j(m) - \pi_0^j(m-1)$, $\forall 1 \leq i, j, m, n \leq I$.

The *monotonicity* assumption *(A1)* states that adoption is rivalrous and thus payoffs decline monotonically in the number of adopters. Rival adoption hurts both firms that have adopted and firms that have not adopted. This reflects the presumption that the new technology opens a new market that has to be shared among adopters, and that non-adopters lose patients as rival hospitals become more technologically advanced. Hence, the game payoff Π^i is increasing in rivals' adoption times. I assume that there are always *positive returns (A2)* to adoption. Firms can always enjoy higher flow profits being an adopter than being a non-adopter, meaning that adoption always weakly increases flow profits at the margin: $\pi_1^i(n) \geq \pi_0^i(n-1)$. More amply, the *stand-alone incentive* to adopt is always positive. Assumption *(A3)* says that there are *decreasing returns* to adoption. That is, the marginal benefit to adoption declines with the rank of adoption. The more firms have already adopted, the less there is to gain from adoption. Assumption *(A4)* requires that the *profitability order* be invariant to the rank of adoption. If firm A gains more from adopting than firm B when one other firm has adopted, then it also gains more from adopting when two other firms have adopted, etc.. Finally, I make the following assumption regarding the cost function:

A5: (cost function decreasing, convex and bounded)

(i) $C(t) > C(t+1)$.

(ii) $C(t) - C(t+1) > C(t+1) - C(t+2)$.

(iii) $\exists t < \infty$ *such that* $C(t) < (\pi_1^i(i) - \pi_0^i(0))/(1-\beta)\ \forall i$.

The *cost function (A5)* is assumed to be falling exogenously over time at a decreasing rate. I also assume that the cost falls eventually to a level such that the gains from adoption are higher than the cost.

3.2 Discussion

Assumption *(A5)* insures that all firms adopt in finite time. The intuition is that if a firm were never to adopt, then the continuation value of not adopting must always be higher than that of adopting. Proposition 1 in the appendix shows that this is ruled out by assumption *5(iii)*. Assumption *5(iii)* has a straightforward economic interpretation. I require that costs fall to such an extent that even if all firms have adopted the technology, flow profits are higher than if no firm had adopted the technology.

Define $\bar{t}$ as the earliest time such that the least profitable firm has an incentive to adopt when all other firms have adopted. Assumption *(A5)* then implies that in any subgame starting $t \geq \bar{t}$, all firms not yet having adopted will adopt immediately. Consider a subgame starting at some $t \geq \bar{t}$ where $(I - i)$ firms have adopted. Suppose one of the remaining firms adopts at $t' > t$. Then it can always increase its payoffs by adopting at $t' - 1$. Hence, all firms will adopt immediately at t. This enables me to solve the model backwards from $\bar{t}$. The endpoint $\bar{t}$ can be computed for a given payoff structure and cost process. It is the smallest t where the marginal increase in period return when adopting $I - th$ is greater than the cost saving when delaying adoption to time $t + 1$.

With firms moving simultaneously the solution concept of subgame perfect equilibrium does not always generate a unique prediction regarding the adoption times and the identities of adopters. In this model of technology adoption, situations similar to an entry model (Bresnahan and Reiss (1991) Berry (1992)) can arise, where the number of adopters can be predicted, but not their identity. In other situations the identity of the first adopter may be known, but it cannot be predicted in which period the first adoption will occur. Whether the first adoption occurs in a given period or a later period, depends on the equilibrium strategies being played in the ensuing subgames. To address this issue, I introduce an assumption regarding the timing of decisions:

A6: (sequential moves) At each period t firms sequentially make the decision whether to adopt. The firm with the $i-th$ largest marginal benefit to adopt $(\pi_1^i(n) - \pi_0^i(n-1))$ moves $i - th$.

The *sequential moves (A6)* addresses the potential multiplicity in the simultaneous move discrete time game. The *sequential moves* assumption can be justified, because it produces the same order of adoptions as if time periods between moves were sufficiently small. The intuition is that if firm A receives a larger increase in period payoffs from adoption than firm B, and both firms face the same cost schedule, then at every point in time the benefit from adopting first today is larger for firm A than for firm B. If time periods are short enough, there will exist a period where firm A prefers to adopt first and firm B does not. For the case $I = 2$ this idea is formalized in Proposition 2 in the appendix.[7]

The *sequential moves* assumption yields a unique equilibrium of the discrete time game. Since all firms adopt in finite time, the game is equivalent to a finite horizon game of complete information and the equilibrium can be computed using a simple recursive algorithm. This is also computationally less burdensome than solving the continuous time game.

The illustrate the algorithm, order the firms according to their profitability. Thus i represents the $i-$th most profitable firm. Consider the least profitable firm I. At $\bar{t} - 1$ firm I knows that all players will adopt next period, regardless of the history of play. If $h_{\bar{t}}^I = (0, 0, ...0)$, i.e. firm I has not adopted, it adopts if the increase in profits minus costs when adopting today versus profits from not adopting outweighs discounted costs from adopting next period. This way, I can compute the value for each history before firm I makes its decision. Thus, firm $I - 1$ knows the continuation value of adopting versus not adopting and chooses its action accordingly. Going backwards, I compute the continuation value for all other players for every history in period $\bar{t} - 2$. I repeat this until period $t = 1$. This yields the history of equilibrium play.

The incentives for a hospital in this model can be summarized as follows. A hospital has an incentive to delay adoption, because the new technology becomes cheaper over time:

[7] For a similar argument see Riordan (1992) who starts with an alternating move game on an arbitrarily fine grid.

$C(t) > \beta C(t+1)$. On the other hand it wants to adopt sooner because adoption generates an increase in period returns, $\pi_1^i(n_t) - \pi_0^i(n_t - 1)$. A monopoly hospital weighs the benefit of higher period payoffs when adopting today against the cost-saving when delaying adoption. The same holds for a hospital in a market where all its rivals have already adopted. If $\pi_1^i(n_t) - \pi_0^i(n_t - 1) > C(t) - \beta C(t+1)$, we say that hospital i has a *stand-alone* incentive to adopt.

Further, a hospital may have an incentive to adopt, because it may change its rivals incentive to adopt due to the *decreasing returns* assumption. Conversely, there is a cost of waiting, because a rival may adopt which has a negative impact on the hospital's own payoffs and will delay its own adoption time. To illustrate this, consider a duopoly market with two identical firms $i = A, B$. The first adopter will enjoy the monopoly profits from adoption until costs have fallen enough such that the *stand-alone* incentive justifies the second adoption. Define the second adoption time determined by the *stand-alone* incentive as T_2^i. Taking this as given, the best response by the first firm would be an adoption time $T_1^i \leq T_2^i$ where the *stand-alone* incentive justifies the first adoption. The first adopter would enjoy higher profits than the second adopter because $\Pi^1(T_1^i, T_2^i) \geq \Pi^2(T_1^i, T_2^i)$.[8] However firm 2 would in fact prefer to *preempt* firm 1 if $\Pi^2(T_1^i - 1, T_2^i) > \Pi^2(T_1^i, T_2^i)$. Hence, the equilibrium first adoption time $\bar{T}_1^i$ must satisfy $\Pi^2(\bar{T}_1^i - 1, T_2^i) \leq \Pi^2(\bar{T}_1^i, T_2^i)$. The first adoption time $\bar{T}_1^i$ is then determined by the advantage of being the leader over being the follower, $\pi_1^i(1) - \pi_0^i(1)$. This is the *preemption incentive*.

Now consider the case where firm A is more profitable than firm B: $\pi_1^A(n) > \pi_1^B(n)$. Then firm A's *stand-alone* incentive is greater than firm $B's$ and $T_2^A \leq T_2^B$. This implies that it becomes less attractive for firm B to preempt firm A, because firm B would enjoy monopoly profits for a shorter period of time. This relaxes the constraint $\Pi^2(\bar{T}_1^A - 1, T_2^A) \leq \Pi^2(\bar{T}_1^A, T_2^B)$ and firm A will adopt weakly later. When $\pi_1^A(n)$ is large enough relative to $\pi_1^B(n)$, then the stand-alone incentive for firm A will justify adoption at such an early time, such that the preemption constraint will not bind anymore: If the heterogeneity in flow payoffs is large

[8] The following argument is adopted from Fudenberg and Tirole (1985). Note that $\Pi^1(T_1^i, T_2^i) \geq \Pi^1(T_2^i, T_2^i)$, because T_1^i is a best response. Note that $\Pi^1(T_2^i, T_2^i) = \Pi^2(T_2^i, T_2^i)$ because firms are identical and finally $\Pi^2(T_2^i, T_2^i) \geq \Pi^2(T_1^i, T_2^i)$, because payoffs are declining in rivals' adoption times.

enough, the first adoption time is determined by firm A's *stand-alone* incentive to adopt first: $\pi_1^A(1) - \pi_0^A(0)$

In the next section I describe an estimation technique that enables me to quantify these effects.

4 Estimation

In this section I specify the profit and cost functions. I propose an estimation technique and present the parameter estimates.

4.1 Specification

I observe L independent markets, with I^l firms operating in market l. Each firms i's adoption year A^{il} and a set of market and firm characteristics $X = [\mathbf{W}^i, \mathbf{Z}]$ is observed, where $\mathbf{W}^i$ is a vector of firm specific variables and $\mathbf{Z}$ a vector of market level demand shifters. I allow for an additive component in the payoff function ε^i that is unobserved by the econometrician, but observed by all firms in the market. The unobserved component ε^i is drawn independently across markets from a strictly monotonic and continuous distribution function F. It may be correlated across firms within a market with coefficient of correlation ρ.

I consider the following parametric equations, describing the payoffs when not having adopted, when having adopted, and the cost function:[9]

$$\begin{aligned} \pi_0^i(n,\theta) &= \alpha_0 + \mathbf{Z}\boldsymbol{\gamma_0} + \mathbf{W}^i\boldsymbol{\mu}_0 + \delta_0 \cdot \log(n+1) \\ \pi_1^i(n,\theta) &= \alpha_1 + \mathbf{Z}\boldsymbol{\gamma}_1 + \mathbf{W}^i\boldsymbol{\mu_1} + \delta_1 \cdot \log(n) + \varepsilon^i \\ C(T^i) &= \bar{c} \cdot \lambda^{T^i} \end{aligned} \tag{1}$$

Here n is the number of firms that have adopted and $\theta = (\alpha_0, \alpha_1, \delta_0, \delta_1, \boldsymbol{\mu}_0, \boldsymbol{\mu}_1, \boldsymbol{\gamma}_0, \boldsymbol{\gamma}_1, \bar{c}, \beta, \lambda, \rho)$

[9] Flow profits that satisfy Asssumptions 1-5 can arise from alternative specifications. One example is a linear Cournot model in the stage game, where adoption of the new technology reduces marginal cost (Quirmbach, 1986). Another example, probably more appropriate for the hospital industry, would be a constant price cost margin toghether with logit demand system, in which the new technology increases the mean utility of choosing the hospital.

is the vector of model parameters. I rescale $\mathbf{W}^i$ and $\mathbf{Z}$ such that they only take on positive values.

The assumptions regarding *monotonicity* and *decreasing returns* hold whenever $\delta_1, \delta_0 \leq 0$, and $(\delta_1 - \delta_0) \leq 0$. Thus the benefit of adoption declines with increasing competition. The number of adopters has a stronger negative of effect on adopters than on non-adopters. Sufficient conditions for the assumption ssumption *positive returns* to hold, are that $(\boldsymbol{\mu}_1 - \boldsymbol{\mu}_0)$, $(\boldsymbol{\gamma}_1 - \boldsymbol{\gamma}_0) > 0$, $(\alpha_1 - \alpha_0) + (\delta_1 - \delta_0) \cdot \log(I) > 0$, and that the support of F is restricted to the positive real line. I assume that F is known. The linear formulation of payoffs in which the competitive effect is symmetric across firms ensures that the assumption regarding the *profitability order* holds. The *cost function* converges to zero at a decreasing rate when $\lambda \in (0, 1)$, satisfying assumptions *A5(i-ii).*

With the cost function converging to zero, assumption *A5(iii)* implies the following restriction, which imposes a lower bound on δ_1 relative to $\alpha_1 - a_0$:

$$\alpha_1 - a_0 + \delta_1 \cdot \log(I) + \mathbf{W}^i(\boldsymbol{\mu}_1 - \boldsymbol{\mu}_0) + \mathbf{Z}(\boldsymbol{\gamma}_{\mathbf{1}} - \boldsymbol{\gamma}_{\mathbf{0}}) > 0$$

The parameter vector of interest θ is point identified if two parametric specificiations are not observationally equivalent. The identification of cost and payoff parameters relies on functional form. However it is useful to discuss the implications from the model that allow us to learn about the payoff function. Let

$$\Delta\pi^i(n, \theta) = \pi_1^i(n, \theta) - \pi_0^i(n - 1, \theta) \tag{2}$$

be firm i's the marginal gain from adopting $n - th$. If firm i adopts last at T^i, it must hold that

$$\Delta\pi^i(I, \theta) - \bar{c} \cdot \lambda^{T^i}(1 - \beta\lambda) \geq 0 \tag{3}$$

$$\Delta\pi^i(I, \theta) - \bar{c} \cdot \lambda^{T^i - 1}(1 - \beta\lambda) < 0 \tag{4}$$

Only *relative* profits $\Delta\pi^i(I, \theta)$ enter this condition. So we can only learn about $(\alpha_1 - \alpha_0, \delta_1 - \delta_0, \boldsymbol{\mu}_1 - \boldsymbol{\mu}_0, \boldsymbol{\gamma}_{\mathbf{1}} - \boldsymbol{\gamma}_{\mathbf{0}})$, the differences of the flow profit parameters. This is not surprising as it is known from discrete choice models that only relative payoffs are identified.

The subgame perfect solution concept imposes another restriction that can be used to separately identify the parameters δ_0 and δ_1. If I observe a large sample of duopoly markets, I can learn about the stand alone incentive $\Delta\pi^2(2,\theta) = \pi_1^2(2,\theta) - \pi_0^2(1,\theta)$ and thus the parameters $(\alpha_1 - \alpha_0 + \delta_1 - \delta_0, \boldsymbol{\mu}_1 - \boldsymbol{\mu}_0, \boldsymbol{\gamma_1} - \boldsymbol{\gamma_0})$ from the second adopters. As discussed in the previous section, in markets where the two hospitals are similar in terms of their characteristics, the first adoption time will be determined by the *preemption* incentive $\pi_1^2(1,\theta) - \pi_0^2(1,\theta)$, and thus by the parameters $(\alpha_1 - \alpha_0 - \delta_0, \boldsymbol{\mu}_1 - \boldsymbol{\mu}_0, \boldsymbol{\gamma_1} - \boldsymbol{\gamma_0})$. If the first hospital is sufficiently more profitable, its adoption time will again be determined by its *stand-alone* incentive $\Delta\pi^2(1,\theta) = \pi_1^1(1,\theta) - \pi_0^1(0,\theta)$ and the parameters $(\alpha_1 - \alpha_0, \boldsymbol{\mu}_1 - \boldsymbol{\mu}_0, \boldsymbol{\gamma_1} - \boldsymbol{\gamma_0})$. The hospital gains enough from adoption such that it adopts at a sufficiently early point in time where its rival prefers to be the follower and adopt later on.

The key argument is that with a cross-section of duopoly markets, the coefficients $\alpha_1 - \alpha_0, \delta_0, \delta_1$ can be estimated separately. The intuition can be summarized as follows. Adding a constant to δ_1 and δ_0, leaves $\delta_1 - \delta_0$ unchanged, and the marginal benefit of adopting last, $\pi_1(2) - \pi_0(1)$ is unaffected. However, the relative benefit of being the leader versus being the follower in a given period, $\pi_1(1) - \pi_0(1)$, changes. The level of δ_0 and δ_1 influences preemption incentive and thus adoption time of the first adopter whereas it has no effect on the second adoption time.

The variation of observables $[\mathbf{W}, \mathbf{Z}]$ and adoption times across markets determines the parameters $\boldsymbol{\mu}_1 - \boldsymbol{\mu}_0, \boldsymbol{\gamma_1} - \boldsymbol{\gamma_0}$. A continuum of combinations of $\bar{c}$ and the discount factor β yield the same optimality conditions in (3) and (4). The hospital industry literature (e.g. Steinberg and Evens (1988)) uses an interest rate from $10 - 12$ percent for cost calculations. Accounting for inflation I fix the discount factor at .94.

I assume that the distribution F of the unobservable profitability shock ε^i is lognormal. Note that the mean and variance of the unobservable are not identified separately from the parameters $\alpha_1 - \alpha_0$ and $\bar{c}$ respectively. I fix these parameters such that the logarithm of the distribution has mean zero and variance one. Having fixed the variance and the discount factor, the cost parameter $\bar{c}$ can be estimated as well.

I now illustrate the role of the unobservable ε^i. First, it accounts for unobserved payoff differences across firms. In absence of such an error we would be able to predict behavior perfectly. The idea is similar to Rust (1994), in that the optimal adoption time for each firm is deterministic for the participants in the market but random from the standpoint of the econometrician. Note that due to the discrete time nature of the model and data, (3, 4) and the preemption conditions yield a set of inequalities, and thus only bounds on the parameters. Making a distributional assumption about F allows me obtain point estimates of the parameters. Finally it allows me to compute expected adoption times for hospitals that have not adopted at the end of my sample.

Following Berry (1992) I allow for within market correlation of ε^i :

$$\varepsilon^i = \exp(\sqrt{(1-\rho^2)}\nu^i + \rho\nu^l)$$

Here ν^i is the firm specific component and ν^l the market specific component of the profitability shock. I assume that both are distributed i.i.d standard normal. I restrict ρ to lie on the interval $[-1, 1]$. With this specification the mean and variance of ε^i are independent of ρ.

There are two possible explanations for diffusion when costs fall over time. When there is no firm heterogeneity ($\rho = 1, \boldsymbol{\mu}_1 - \boldsymbol{\mu}_0 = 0$), a competitive effect will cause diffusion, because the marginal incentive to adopt changes with the rank of adoption. In absence of a competitive effect (e.g. $\delta_1 - \delta_0 = 0$), firm heterogeneity in payoffs will lead to different adoption times, because different firms have different *stand-alone* incentives. These two explanations can be distinguished as they have different cross sectional implications for adoption times. Consider first the case of no heterogeneity ($\rho = 1, \boldsymbol{\mu}_1 - \boldsymbol{\mu}_0 = 0$). The adoption times in the two markets (T_1, T_2) and (T_1', T_2') must satisfy $T_1 \geq T_1'$ if and only if $T_2 \geq T_2'$; both firms within a market gain the same from adoption. If the first firm gains less in adoption from than the first firm in the other market, the second firm in one market must also gain less than the second firm in the other market. This implies that the second adoption time is a monotonically increasing function of the first adoption time everywhere. On the other hand, if there were no competitive effect and everything driven by heterogeneity, the probability of an adoption occurring would be independent of the number of adoptions that have already occurred. I will not test these nonparametric implications, but the argument shows that the identification of the competitive effect is not solely due to functional form.

4.2 A method of moments estimator

I now introduce a method to estimate the technology adoption model. The model does not yield a closed firm solution for the expectation of the vector of adoption times conditional on the market and firm specific observables and the model parameters. I propose a Method of Simulated Moments (MSM) Estimator (McFadden (1989), Pakes and Pollard (1989)) that does not require to compute the expectation of adoption times.

Let $\theta = (\alpha_1 - \alpha_0, \delta_0, \delta_1, \boldsymbol{\mu}_1 - \boldsymbol{\mu}_0, \boldsymbol{\gamma_1} - \boldsymbol{\gamma_0}, \bar{c}, \lambda, \rho)$ be the vector of parameters to be estimated with cardinality $|\theta| = D$. Let $X_l = [\mathbf{W},\ \mathbf{Z}]$ be exogenous market and firm specific variables and A the vector of adoption years. I compute a J-dimensional vector $\hat{\psi}(A)$ of empirical moments. For every market l I obtain S draws of an I_l-dimensional vector ε of profitability shocks from the distribution F. For a given parameter-vector θ the model is solved recursively for every draw s and every market l and I compute a vector of simulated adoption times $A_s(X, \theta)$. The simulation draws are held fixed for different parameter vectors. I compute the average simulated moments $\tilde{\psi}_S = \frac{1}{S}\sum_{s=1}^{S} \psi(A_s)$. Let $g = \frac{1}{L}\sum_{l=1}^{L}(\hat{\psi} - \tilde{\psi}_S)_l \otimes f(X_l)$ be the vector of moment conditions, where $f(X_l)$ is a $K-$dimensional vector function of the market and firm specific exogenous variables. The MSM-estimator $\hat{\theta}$ is defined as the minimizer of the weighted distance between observed and simulated moments:

$$\hat{\theta} = \underset{\theta}{\operatorname{argmin}}\, g'\Omega g$$

Here Ω is a $J \times K$-dimensional symmetric weight matrix. The esimator $\hat{\theta}$ is consistent and $\sqrt{L}(\hat{\theta} - \theta_0)$ is asymptotically normally distributed with zero mean and covariance matrix $(1 + \frac{1}{S})(E\frac{\partial}{\partial\theta}g'\Omega E\frac{\partial}{\partial\theta}g)^{-1}E\frac{\partial}{\partial\theta}g'\Omega Egg'\Omega E\frac{\partial}{\partial\theta}g(E\frac{\partial}{\partial\theta}g'\Omega E\frac{\partial}{\partial\theta}g)^{-1}$. The efficiency of the estimator can be improved by employing an optimal weight matrix $\Omega = (Egg')^{-1}$. The asymptotic distribution of $\sqrt{L}(\hat{\theta} - \theta_0)$ then becomes $(1 + \frac{1}{S})(E\frac{\partial}{\partial\theta}g'\Omega E\frac{\partial}{\partial\theta}g)^{-1}$. The optimal weight matrix is computed using a consistent estimate of θ. Estimates of the standard errors are obtained by replacing the terms in the expression for the covariance matrix are with consistent estimates.

The moment selection is guided by the need to capture the dynamics of adoption. I also require that the same set of moments is employed for every market, regardless of the number of hospitals or the number of adoptions actually observed. Thus, the moment selection is similar to Berry (1992), who deals with varying numbers of potential entrants across markets. The final specification includes the firm specific variables hospital size (measured by the logarithm of the number of beds), a dummy for nonprofit hospitals and a dummy for for-profit hospitals (community hospitals being the reference category), and market variables population and per capita income. This implies that a total of 11 parameters is estimated and at least as many moment conditions are required. I first select the following 8 moments: The number of adoptions by the end of 1986, the number of adoptions by the end of year 1987, etc. until the number of adoptions by the end of 1993. In order to capture the effect of market specific variables, I interact the number of adopters by 1993 with the market specific observables, population and per capita income. To capture the effect of hospital size, I add a moment defined as whether the largest hospital has adopted by 1993. Finally, to capture the effect of organizational type I add one moment defined as the number of nonprofits that have adopted by 1993, and one moment defined as the number of forprofits that have adopted by 1993. This results in a total of 13 moments. Depending on the specification, this yields at least two to six overidentifying restrictions. Higher order moments could also be employed.

4.3 Parameter estimates

Table 3 shows the parameter estimates for three specifications. The first specification includes no firm characteristics, such that firms are identical up to the realization of the profitability shock ε^i. The proxies for demand are the logarithms of population and per capita income. Specification 2 includes firm characteristics such as hospital size (the log of the number of beds), and organizational form, a dummy for nonprofit and for-profit. The reference case is a community hospital. In the third specification I allow for within market correlation ρ of the unobservable profitability shock ε^i. Standard errors are reported in parentheses beneath the estimates. The number of simulation draws per market is 20.

All of the parameters are estimated very precisely. Adopting increases period payoffs evaluated at the median values of population and per capita income by 25 units, about 5.5 percent of the adoption cost when adopting at time zero. The real cost declines at a rate of about 3 percent, implying that it is reduced by 25 percent after about nine and a half years and by 50 percent after about 22 and a half years. The real 'street price' of a premium high field MRI unit fell at a rate of approximately 4.5 percent over the period from 1983 to

1993 (Bell (1996)). Since the model also includes installation cost, which probably increased over time, this result also validates the model ex-post. Payoffs decline significantly with the number of adopters, with the effect on adopters about 4 times stronger than that on non-adopters. I find that nonprofit firms have a stronger incentive to adopt the new technology than for-profit hospitals. This corresponds to recent findings that nonprofit hospitals act as if they have lower marginal costs (Gaynor and Vogt (2003)).

The relative economic significance of the estimated coefficients can be examined by conducting simulation exercises. I fix the the market characteristics at their median values, and consider the base case with all hospitals being community hospitals of median size. First, I consider a 10% percent increase in population at the median value. This accelerates adoption by 1.2 months on average. A 10% increase in per capita income however accelerates adoption insignificantly by about 3 days. To illustrate the importance of the interaction parameters δ_0 and δ_1, I compare the adoption times predicted by the estimated model relative to those when $\delta_0 = \delta_1 = 0$. This removes any strategic considerations by the hospitals and they act as if they were facing independent demand curves. The effect is best illustrated in the duopoly case. The first adoption would occur 1 year later on average, whereas the second adoption occurs about 2 years earlier. The first adoption occurs later, because the preemption incentive no longer forces the first firm to adopt sooner.[10] The second adoption occurs sooner, because under this scenario the marginal benefit of adopting is the same as adopting first. The difference between the first and second adoption times is purely driven by the heterogeneity in payoffs.

To assess the fit of the model, I simulate the model and average the adoption rates across simulations. The results are presented in Figures 2 and 3. Figure 2 compares the simulated adoption rates to the observed adoption rates overall. The model slightly overpredicts adoption at the beginning of the observed period and underpredicts after 1987. Figure 3 compares the simulated versus the observed series by market size. The model underpredicts adoption rates in monopoly and duopoly markets, but fits markets with three firms and four firms very well. The model may tend to fit markets with more firms better because more adoptions are observed in these markets and hence most of the identification is obtained

[10] The fact that hospitals have identical characteristics overstates the preemption effect.

from these markets.

In the next section I use the estimated parameters to quantify the effect of competition on adoption times.

5 The effect of competition on MRI adoption

As the effect of new technologies and hospital competition on health care cost has received wide attention. While the results provided here do not provide direct evidence for the impact of a new technology on health care costs or overall welfare, the framework enables me to assess how competition affects the timing of adoption and industry profits from adoption. In particular, I perform two counterfactual experiments in which I decompose the effect of competition into a business stealing and a preemption effect.

5.1 Maximizing industry profits

I first examine the effect of competition by comparing the adoption times under competition to those chosen by an industry regulator, who wishes to maximize industry profits. To achieve this, the regulator takes into account the effect on the firms having adopted as well as the firms not having adopted, which makes knowledge of the parameter δ_0 essential for this analysis. The regulator thus eliminates both, the business stealing and the preemption effect. Order the firms $i = \{1, 2......, I\}$ according to their profitability. Naturally, the optimal solution requires more profitable firms to adopt sooner than less profitable firms (as long as competitive effects are symmetric). The industry regulator chooses adoption times $\mathbf{T} = \{T^1, T^2, ..., T^I\}$ to maximize industry profits:

$$\begin{aligned}\Pi^R_{(\mathbf{T})} = & \\ & \sum_{i=1}^{I}\sum_{n=0}^{I} \mathbf{1}_{\{i>n\}} \pi_0^i(n) \cdot \frac{\beta^{T^n} - \beta^{T^{n+1}}}{1-\beta} \\ & + \sum_{i=1}^{I}\sum_{n=0}^{I} \mathbf{1}_{\{i\leq n\}} \pi_1^i(n) \cdot \frac{\beta^{T^n} - \beta^{T^{n+1}}}{1-\beta} \\ & - \sum_{n=1}^{I} \beta^{T^n} \cdot C(T^n)\end{aligned}$$

where $T^0 = 0$ and $T^{I+1} = \infty$. I define the gains from adoption $\Delta\Pi(\mathbf{T})$ as the difference between industry profits under adoption times $\mathbf{T}$ and profits when firms do not adopt at all (which is normalized to zero). The measure of profit loss ΔV is then defined as the percentage increase in the gains from adoption when moving from the competitive regime with adoption times $\mathbf{T}^*$ to the regulatory regime with adoption times $\mathbf{T}^R$:

$$\Delta V = \frac{\Delta\Pi(\mathbf{T}^R) - \Delta\Pi(\mathbf{T}^*)}{\Delta\Pi(\mathbf{T}^*)}$$

To assess the profit loss, I compute the implied adoption times under the competitive and the regulatory regime, as well as the corresponding ΔV as defined above for each market.

I compute the average of these figures within a group of markets, where a group is defined as the number of hospitals in a market. Table 4 describes the effect of the regulatory solution compared to the competitive solution. Obviously, nothing changes in the monopoly markets, so I report results for duopoly, three-firm and four-firm markets only. The standard deviations are reported in parentheses. The top four rows in Table 4 describe how the adoption times change on average in these markets. Because the returns to adoption decline with the rank of adoption of firms and the negative impact on competitors' profits is larger, adoption times are delayed more the lower the adoption rank. The percentage numbers in the last row of Table 4 presents estimates of the profit loss. The increase in net discounted industry-profits under the regulatory regime would be 1.86% (2 firms), 3.86% (3 firms), and 5.56% (4 firms). An increase in the demand variables lowers the effect of a regulatory solution. The profit loss is mitigated by the higher mean demand levels in counties with a larger number of hospitals. The effect can be decomposed into a profit effect and a cost effect. The total effect on discounted flow profits is negative. The cost savings due to delayed adoption outweighs the foregone profits by delayed adoption.

5.2 The role of preemption

I now examine effect of the optimal timing on the hospital payoffs. The aim is to quantify how the advantage of being an early adopter affects the corresponding strategic behavior and profits. In particular, I want to quantify the effect of preemption. Preemption is the phenomenon that a firm adopts earlier than it would were it only to account for its stand alone incentive just to prevent its rival from adopting. The effect of preemption on adoption times and profits has received wide attention in the theoretical literature (Fudenberg and Tirole 1985, Riordan, 1992). I compare payoffs in the subgame perfect equilibrium to payoffs if firms were playing an 'open-loop' or a Nash equilibrium strategy. In a Nash equilibrium firms precommit to their adoption times (Reinganum, 1982), which removes the incentive to preempt. A vector of adoption times T^{NE} constitutes a 'pre-commitment' or 'open loop' equilibrium if

$$\Pi^i(T^{NE,i}, T^{NE,-i}) \geq \Pi^i(T^i, T^{NE,-i})$$

for all i. Again, there may be multiple pure strategy equilibria. For the analysis here, I choose the equilibrium where the most profitable firm moves first. The adoption time $T^{NE,i}$ of the $i-th$ most profitable firm i must satisfy

$$\bar{c} \cdot \lambda^{T^{NE,i}}(1-\beta\lambda) - \Delta\pi^i(i,\theta) > 0 \geq \bar{c} \cdot \lambda^{T^{NE,i}-1}(1-\beta\lambda) - \Delta\pi^i(i,\theta)$$

This allows me to compute the Nash equilibrium adoption times $T^{NE,\cdot}$.

Table 5 compares the adoption times and welfare gains of the Nash equilibrium play relative to the subgame perfect equilibrium outcome. Again, nothing changes in monopoly markets. Further, the adoption times of the last firm do not change, as it makes only a marginal decision even in the subgame perfect equilibrium. The effects here are much smaller, with the first adoption being delayed by less than one year. The gain in profits is only about one sixth of the profit maximizing regime.

The results from these counterfactual experiments let me conclude that preemption has a significant but small effect, and most of the profit loss due to competition is due to a regular 'business stealing' effect, caused by firms simply not taking into account the negative impact their adoption has on other firms.

6 Conclusion

In this paper I studied a timing game of technology adoption by US hospitals. I develop an estimable model that allows me to recover the structural parameters of the timing game. I find that there is a strong competitive effect on hospital profits. Knowledge of the game parameters enables me to conduct counterfactual experiments to quantify the effect of competition on adoption times and hospital profits. Results of these experiments show that the competitive solution leads to significantly earlier adoption times than we would see under a regime that maximizes industry profits. The cost to discounted net industry profits ranges from 1.86% in duopoly markets to 5.56% in markets with four hospitals. The bulk of this cost is due to regular business stealing. The 'preemption' effect accounts for a small share of this change.

The analysis carried out in this paper can be extended along various dimensions. For a complete welfare analysis, the demand side should analyzed. Using patient discharge data a demand system could be estimated. This way, a better measure of hospital profits could be obtained, and the cost of competition to profits could be weighed against the potential benefits of earlier adoption to patients.

The model bears some features which may not be accurate for the hospital environment. Flow profits are constant over time and there is no uncertainty about future payoffs and costs. Incorporating more realistic features along these dimensions may make the solution and estimation of this model considerably more complicated.

7 Appendix

Here I show that given the assumptions about the payoffs, all firms will adopt in finite time and that the order of adoption is unique as time periods become sufficiently short.

Proposition 1 *Given assumptions (A1) to A(5) all firms will adopt in finite time.*

Proof. Suppose $I-1$ firms have adopted at time t. Let I be the least profitable firm. Firm I will adopt if and only if the benefits to adopting exceed the costs:

$$\pi_1^I(I) - \pi_0^I(I-1) > C(t) - \beta C(t+1) \tag{5}$$

By the *positive returns* and the *monotonicity* assumptions, the term on the left is always positive and given our assumptions on the cost function *A5(iii)* there exists a $\bar{t} < \infty$ such that this inequality holds. Now suppose $I-2$ firms have adopted at some time $t' > \bar{t}$. Denote the remaining two firms $i = j, k$. Then firm j knows that if it adopts it triggers immediate adoption by the last remaining firm k and vice versa. So either firm will always want to adopt, if the benefit from adopting is greater than the maximum benefit from not adopting. Let $V_0^i(I-2)$ be the continuation value of not adopting when $I-2$ firms have adopted and $V_1^i(I-1)$ be the continuation value when having adopted along with $I-2$ other firms. For either of the two firms never to adopt, the continuation value of not adopting must be greater than that of adopting for all t:

$$\pi_0^i(I-2) + \beta V_0^i(I-2) \geq \pi_1^i(I-2) - C(t) + \beta V_1^i(I-2)$$

So for firms $i = j, k$ never to adopt it must hold for all t:

$$\pi_1^i(I-1) + \beta \frac{\pi_1^i(I)}{1-\beta} - C(t) < \frac{\pi_0^i(I-2)}{1-\beta}$$

By *monotonicity* this implies:

$$\frac{\pi_1^i(I)}{1-\beta} - C(t) < \frac{\pi_0^i(I-2)}{1-\beta} \tag{6}$$

or

$$\frac{\pi_1^i(I) - \pi_0^i(I-2)}{1-\beta} < C(t) \tag{7}$$

The first term represents the payoff from immediate adoption. Since it triggers adoption from the remaining firm, it will earn $\pi_1^i(I)$. We need to find a $\bar{t}$ such that the inequality is reversed. Similarly, if $I-3$ firms have adopted, all firms will adopt eventually if

$$\frac{\pi_1^i(I) - \pi_0^i(I-3)}{1-\beta} > C(t)$$

for some $t < \infty$. Applying the argument above repeatedly up to a situation where no firm has yet adopted yields

$$\frac{\pi_1^i(I) - \pi_0^i(0)}{1-\beta} > C(t)$$

for all $i = 1.....I$. Assumption *A5(iii)* ensures that this inequality holds and hence, all firms will adopt in finite time. ■

Next, we formalize the idea that when time periods are sufficiently small, the order of adoption will be unique. We first introduce another assumption that rules out preemption at the beginning of the game:

A7: $\pi_1^i(1) - \pi_0^i(I-1) < C(0) - \beta C(1) \ \forall \ i = 1...I$

Assumption *(A7)* along with Assumption *(A5(ii))* implies that there is no adoption at time zero.

We consider the case $I = 2$ with firms A and B. Firm A is more profitable in the sense that

A8 (i) $\pi_1^A(m) - \pi_0^A(m-1) > \pi_1^B(m) - \pi_0^B(m-1)$ and (ii) $\pi_1^A(m) - \pi_0^A(m) > \pi_1^B(m) - \pi_0^B(m)$.

A9: $C(t)$ is continuous.

Proposition 2 *Suppose that (i) $I = 2$, and that (ii) Assumptions 1-5 and 7-9 hold, then at any $t > 0$ there exists an integer $K < \infty$ such that if firms can move at every point on the grid $[t-1, t+\frac{1-K}{K}, t+\frac{2-K}{K}, ..., t]$, the order of adoption is unique.*

Proof. We know that there exists a finite T_2^i such that $\pi_1^i(2) - \pi_1^i(1) > C(T_2^i) - \beta C(T_2^i + 1)$. T_2^i is the best response of firm i conditional upon it being the second adopter. Because firm A is more profitable we know that $T_2^A \leq T_2^B$. In any subgame starting at t with $T_2^A \leq t \leq T_2^B$ and no firm having yet adopted, firm A will adopt immediately because even if firm B adopts it is firm $A's$ best response to adopt immediately. Firm B will follow by adopting at its best response T_2^B. Note that because of the assumptions about the payoff structure of the model (payoffs are independent of the order of adoption) T_2^i is independent of the timing of the first adoption. For any $t < T_A^2$ we can write the payoffs of firm i conditional upon one firm adopting at t and the other firm adopting at its best response. Let $V^A(t, T_2^B)$ be firm $A's$ payoff in the subgame starting at t with A adopting immediately and firm B following at at T_2^B. $V^A(T_2^A, t)$ is firm $A's$ payoff if it adopts second at T_2^A and B adopting immediately. Similarly we define firm B's payoffs as $V^B(t, T_2^B)$ if it adopts second and $V^B(T_2^A, t)$ if it adopts first. Now note that $V^A(t, T_2^B) - V^A(T_2^A, t) > V^B(T_2^A, t) - V^B(t, T_2^B)$ because (i) firm A gains more from adopting by Assumption 7, (ii) it will enjoy that gain for a longer time than firm B as $T_2^A < T_2^B$, and (iii) firm B enjoys higher cost savings by adopting second for the same reason. Note that by *(A7)*: $0 > V^A(0, T_2^B) - V^A(T_2^A, 0) > V^B(T_2^A, 0) - V^B(0, T_2^B)$. Hence, if there is a t such that $V^A(t, T_2^B) - V^A(T_2^A, t) > 0$, then there must be a $t' \leq t$ such that $V^A(t', T_2^B) - V^A(T_2^A, t') > 0$ and $V^A(t'-1, T_2^B) - V^A(T_2^A, t'-1) < 0$. The same holds for firm B. If $V^A(t, T_2^B) - V^A(T_2^A, t) > V^B(T_2^A, t) - V^B(t, T_2^B) > 0$ both firms want to adopt and there are two pure strategy equilibria in this subgame with either firm adopting and the other firm not adopting. If $V^A(t-1, T_2^B) - V^A(T_2^A, t-1) > 0$ and $V^B(T_2^A, t-1) - V^B(t-1, T_2^B) < 0$ then there are two equilibrium outcomes. One involves firm A adopting in period $t-1$, the other one involves A adopting in period t. In which period A adopts depends on the equilibrium played in the subgame at period t. Hence, the order of adoption is unique.

Next, consider the case if $V^A(t-1, T_2^B) - V^A(T_2^A, t-1) < 0$ holds, then no firm wants to adopt in period $t-1$, but both are willing to adopt at time t. We first find a $t_0 \in (0, 1)$ such that firm A is indifferent between being the follower or the leader at $t - t_0$. Suppose both firms are allowed to move at $t - t_0$. Define $\Delta V^A(t, t_0) = V^A(t - t_0, T_2^B) - V^A(T_2^A, t_0)$:

$$\left[\frac{1-\beta^{t_0}}{1-\beta} + \beta^{t_0} \sum_{t_s=0}^{T_2^B - t} \beta^t\right] (\pi_1^A(1) - \pi_0^A(1)) - C(t - t_0) + \beta^{t_0 + T_2^A - t} C(T_2^A)$$

By assumption $\Delta V^A(t, 0) > 0$ and $\Delta V^A(t, 1) < 0$. Since $\Delta V^A(t, t_0)$ is continuous in t_0, there must exist a $\hat{t}^A$ such that $\Delta V^A(t, \hat{t}^A) = 0$. Further, if $\Delta V^A(t, t_0)$ exhibits a local extremum, i.e. $\frac{\partial \Delta V^A(t,t_0)}{\partial t_0} = 0$, we have that

$$\frac{\partial^2 \Delta V^A(t, t_0)}{\partial t_0^2} = -C'(t - t_0)\beta^{-1}(t_0 - 1) - C''(t - t_0) < 0$$

because the cost function is decreasing and convex. Thus, $\Delta V^A(t, t_0)$ is strictly quasi-concave, and $\hat{t}^A$ is unique. Since the value of adopting is greater for firm A, it must hold that $\Delta V^B(t, \hat{t}^A) < 0$. Similarly, we can find a unique $\hat{t}^B$, which must satisfy $\hat{t}^B > \hat{t}^A$ because $\Delta V^B(t, t_0)$ is also quasi-concave and $\Delta V^B(t, \hat{t}^A) < 0$ and $\Delta V^B(t, 0) > 0$. We now find the smallest K such that there exists a $k \in \{1, 2, ..., K\}$ such that

$$\hat{t}^A < t + \frac{k - K}{K} < \hat{t}^B$$

Both firms prefer to adopt first at $t + \frac{k+1-K}{K}$, and only firm A is willing to adopt first at $t + \frac{k-K}{K}$ if the equilibrium at $t + \frac{k+1-K}{K}$ involves firm B adopting first. Hence, two equilibrium outcomes will remain; both involve firm A adopting first, either at $t + \frac{k-K}{K}$ or $t + \frac{k+1-K}{K}$. ■

I conjecture that a similar argument holds for $I > 2$. However a simple inductive argument cannot be applied. This can be illustrated for the case $I = 3$. In a subgame with the two less profitable remaining firms remaining, the second adoption may occur sooner than in a subgame where one of the remaining firms is the most profitable. By adopting first at time t, the most profitable firm may induce an earlier second adoption. Thus it is not straightforward to show that the continuation value when adopting is always highest for the most profitable firm.

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Table 1: Cross Tabulation: # of MRIs versus # of hospitals 1993

	# of Hospitals									
	1		2		3		4		Total	
# of MRI by 1993										
0	45	(77.6%)	61	(67.0%)	43	(48.8%)	24	(34.8%)	173	(56.5%)
1	13	(22.6%)	25	(27.5%)	32	(36.4%)	23	(33.3%)	93	(30.4%)
2			5	(5.5%)	13	(14.8%)	14	(20.3%)	32	(10.5%)
3					0	(0.0%)	7	(10.2%)	7	(2.3%)
4							1	(1.4%)	1	(0.3%)
Total	58	(100%)	91	(100%)	88	(100%)	69	(100%)	306	(100%)

Table 2: Summary Statistics: Population and Income

	# of Hospitals			
	1	2	3	4
Population				
Minimum	3,495	3,854	13,074	19,046
Maximum	74,335	272,700	420,806	331,708
Mean	24,089	55,668	89,563	114,680
Median	18,692	40,052	66,255	85,373
Income				
Minimum	9,468	9,754	10,014	9,769
Maximum	33,991	31,195	27,416	25,085
Mean	16,701	16,623	16,548	17,251
Median	16,212	15,914	16,354	17,377
Frequency	58	91	88	69

Table 3: Parameter Estimates

constant	$\alpha_1 - \alpha_0$	11.3400	10.6630	10.574
		(0.3944)	(1.2531)	(0.9752)
# of adopters				
on adopters	δ_1	-4.4250	-4.2670	-3.467
		(0.2205)	(0.8443)	(0.8128)
on non-adopters	δ_0	-0.8057	-0.7782	-0.8475
		(0.0311)	(0.1348)	(0.2093)
cost	$\bar{c}$	410.8200	456.9600	468.54
		(7.1357)	(4.9101)	(6.5589)
	$1/\lambda - 1$	0.0344	0.0368	0.0311
		(0.0018)	(0.0016)	(0.0088)
Demand				
Population	$(\gamma_1 - \gamma_0)_{Pop}$	0.9442	0.6599	0.8950
		(0.0232)	(0.0370)	(0.1706)
Income	$(\gamma_1 - \gamma_0)_{PCI}$	0.0007	0.1923	0.1034
		(0.0021)	(0.0425)	(0.0366)
Hospital characteristics				
Hospital size	$(\mu_1 - \mu_0)_{beds}$		0.9218	0.8369
			(0.0827)	(0.1659)
Nonprofit Dummy	$(\mu_1 - \mu_0)_{NP}$		1.6644	1.6018
			(0.4895)	(0.3995)
For-profit Dummy	$(\mu_1 - \mu_0)_{FP}$		1.3652	0.8813
			(2.3266)	(0.3521)
Market Correlation	ρ			0.5756
				(0.0781)
Observations		306	306	306
Moments		13	13	13

Note: Standard errors are in parentheses. Number of simulations is 20.

Table 4: Regulatory Regime versus Subgame Perfect Equilibrium

	# of Hospitals		
	2	3	4
	$\mathbf{T}^R - \mathbf{T}^*$	$\mathbf{T}^R - \mathbf{T}^*$	$\mathbf{T}^R - \mathbf{T}^*$
1^{st}	1.2747	2.0341	2.5942
	(0.0964)	(0.1204)	(0.1174)
2^{nd}	3.3956	3.9205	4.3043
	(0.0539)	(0.0651)	(0.0975)
3^{rd}		4.2159	4.4493
		(0.0522)	(0.0787)
4^{th}			4.6667
			(0.0674)
ΔV	1.86%	3.86%	5.56%
	(0.09)	(0.15)	(0.21)

Notes: T^*: Adoption time in subgame perfect equilibrium

T^R: Adoption time maximizing industry profits

ΔV: change in industry profits when moving regulatory regime

Standard errors are in parentheses.

Table 5: Nash Equilibrium versus Subgame Perfect Equilibrium

	# of Hospitals		
	2	3	4
	$\mathbf{T}^{NE} - \mathbf{T}^{*}$	$\mathbf{T}^{NE} - \mathbf{T}^{*}$	$\mathbf{T}^{NE} - \mathbf{T}^{*}$
1^{st}	0.4725	0.7613	0.5362
	(0.0846)	(0.1047)	(0.0890)
2^{nd}		0.2046	0.3768
		(0.0462)	(0.0656)
3^{rd}			0.1159
			(0.0388)
4^{th}			
ΔV	0.33%	0.84%	0.91%
	(0.07)	(0.10)	(0.12)

Notes: T^*: Adoption time in subgame perfect equilibrium

T^{NE}: Adoption time in Nash equilibrium

ΔV: change in industry profits when moving to Nash equilibrium

Standard errors are in parentheses.

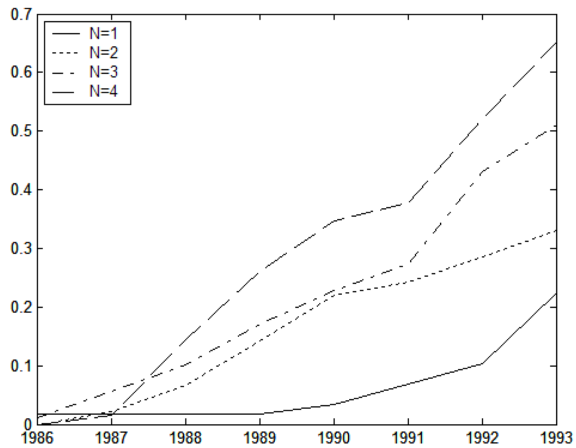

Figure 1: Fraction of markets with at least one MRI

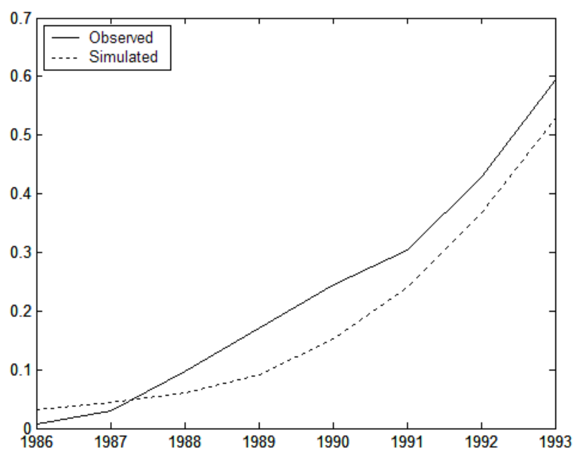

Figure 2: Number of adoptions per market: All markets

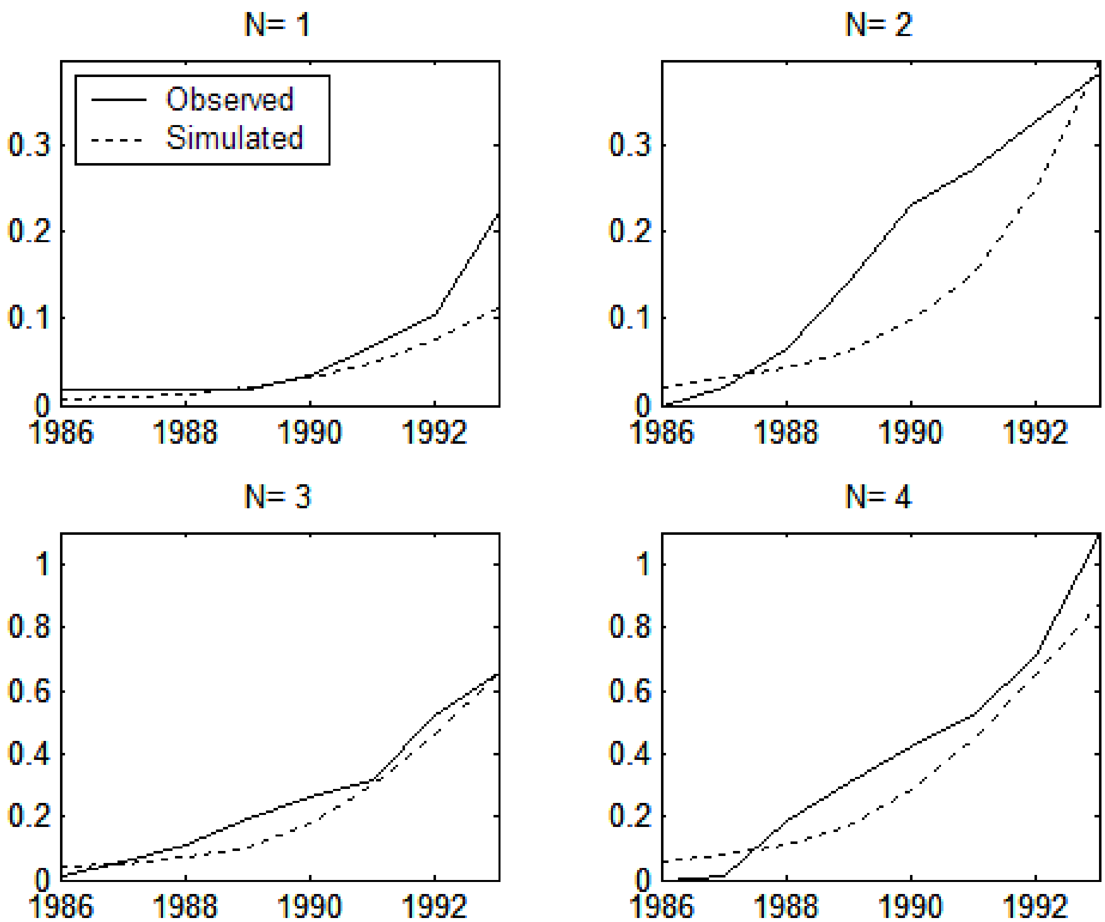

Figure 3: Number of adoptions per market by market size