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Clinical Ambiguity and Conflicts of Interest in Interventional Cardiology Decision Making

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Abstract. ***Problem definition*:** Among the most vexing issues in the U.S. healthcare ecosystem is inappropriate use of percutaneous coronary intervention (PCI) procedures, also known as overstenting. A key driver of overstenting is physician subjectivity in eyeballing a coronary angiogram. Advanced tests such as fractional flow reserve (FFR) provide more precise and objective measures of PCI appropriateness, yet the decision to perform these tests is endogenous and not immune to clinical ambiguity associated with eyeballing. Additionally, conflicts of interest, arising from revenue-generating incentives, play a role in overstenting. ***Academic/practical relevance*:** Conventional wisdom suggests more precise diagnostic testing will help reduce overtreatment. However, the literature rarely recognizes that the testing decision is itself endogenous. Our research highlights the role of endogeneity surrounding interventional cardiology decision making. ***Methodology*:** This study uses stochastic modeling and simulation. ***Results*:** Under a low conflict-of-interest level, the physician performs the advanced test for intermediate lesions. Under a high conflict-of-interest level, however, the physician would perform the advanced test only for high-grade lesions, because of a financial *disincentive*: Performing the advanced test may lower PCI revenue if the test results argue against the procedure. Surprisingly, despite this disincentive, a more revenue-driven physician can be more inclined to perform the advanced test. ***Managerial implications*:** Our model leads to implications for various efforts aimed at tackling overstenting: (1) Attention should be paid not only to the sheer quantity of FFR procedures but to which patients receive FFR procedures; (2) reducing the risk of the advanced test has a behavior-inducing effect, yet a modest risk reduction may lower patient welfare; and (3) offering a bonus to the physician for performing FFR procedures equal to a third of its reimbursement rate will cause only a 5% increase in average physician payment while inducing a 26% decline in overstenting. In addition, we show implementing a bundled payment scheme may discourage the use of FFR procedures and lead to more salient overstenting.

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1. Introduction

Percutaneous coronary intervention (PCI)—the placement of coronary stents—has attracted national attention in recent years (Abelson and Creswell 2012, Carroll 2018, Kolata 2019). A *New York Times* article (Harris 2010) describes one case in point:

> Word quickly reached top executives at Abbott Laboratories that a Baltimore cardiologist, Dr. Mark Midei, had inserted 30 of the company's cardiac stents in a single day in August 2008, "which is the biggest day I remember hearing about," an executive wrote in a celebratory email … Two days later, an Abbott sales representative spent $2,159 to buy a whole, slow-smoked pig, peach cobbler, and other fixings for a barbecue dinner at Dr. Midei's home, according to a report being released Monday by the Senate. The dinner was just a small part of the millions in salary and perks showered on Dr. Midei for putting more stents in more patients than almost any other cardiologist in Baltimore.

According to Steven Nissen, chief of cardiovascular medicine at the Cleveland Clinic, "What was going on in Baltimore is going on right now in every city in

America" (Harris 2010, p. A15). A recent study of 2.7 million PCI procedures from 766 U.S. hospitals found only 53.6% of PCI cases were classified as appropriate, 33.0% of PCI cases were classified as uncertain, and 13.3% of nonacute PCIs were classified as inappropriate (Desai et al. 2015).[1]

The decision to conduct a PCI procedure is usually made by a cardiologist visually assessing a coronary angiogram (eyeballing), a process with significant subjectivity. Several advanced intracoronary tests used in addition to angiography can provide more objective bases for decisions on PCI procedures (see Section 2 for a detailed description of advanced intracoronary tests) and are believed to help reduce overstenting (Tonino et al. 2009). However, although these tests are more precise and objective, angiography still guides the decision to administer them, which is endogenous and not immune to the subjectivity associated with the angiogram-guided clinical decision making.

This situation raises two issues. First, even for an interventional cardiologist without any revenue-generation incentives, making clinical decisions involves ambiguity (Klein 2013), particularly when the decision making is guided solely by a coronary angiogram (see Section 2 for details about the diagnostic process). Clinical ambiguity comes from two sources: (1) the ambiguity in eyeballing the angiogram itself—interoperator and even intraoperator variability is known to exist in a cardiologist's assessment of the severity of a blockage, and (2) the nuance in determining the clinical necessity of PCI even when the interpretation of the angiogram is accurate. Second, a cardiologist with revenue-generating incentives may find it lucrative to justify unnecessary PCI procedures by misstating the angiographic severity of stenosis.[2] This issue is echoed by the remark of Dr. Robert Levine (2009, p. e16(2)) in the *New England Journal of Medicine*: "Even if all physicians were highly ethical and ordered only tests and treatments they deemed truly important, it would take saints not to have their judgment skewed in favor of decisions that will provide them with financial rewards." These two issues correspond to *clinical ambiguity* and *conflicts of interest*, respectively. The former is clinical, whereas the latter is nonclinical and can be influenced by multiple factors such as individual character and organizational culture.[3] Because disentangling conflicts of interest from clinical ambiguity is difficult, even the appropriate use criteria (AUC)—a key initiative aimed at guiding interventional cardiology decision-making—emphasizes uncertainty and nuance intrinsic to clinical practices (Patel et al. 2009, 2012).

By jointly modeling clinical ambiguity and conflicts of interest, our research uncovers important and interesting insights into interventional cardiologists' decision-making process, particularly their decisions about performing advanced intracoronary tests. Two central issues we address in this paper are (1) physicians' patterns in performing the advanced test, and consequently, (2) the implication of the endogenous testing pattern for the use of PCI procedures.

We model the sequential diagnostic and treatment decisions in a cardiac catheterization laboratory (hereafter, cath laboratory). In our model, a physician's utility derives from a weighted sum of patient welfare and the physician's financial gains from diagnosis, optional advanced tests, and PCI procedures. The optimal decision rule is reached by balancing the clinical and nonclinical benefits associated with various courses of diagnosis and treatment against their risks.

Our study leads to an in-depth understanding of physicians' decision making under various conflict-of-interest levels. First, under a relatively low conflict-of-interest level, the physician performs the advanced test when the visually assessed angiographic stenosis is sufficiently close to the stenosis threshold. In essence, the physician performs the advanced test chiefly to mitigate the clinical ambiguity associated with angiogram-guided PCI decision making. However, under a high conflict-of-interest level, a *disincentive* to perform the advanced test exists, because more advanced tests may likely lead to reduced PCI revenue. Thus, the physician performs the advanced test only when the visually assessed angiographic stenosis is sufficiently high. The advanced test—intended to improve PCI decision-making—may end up justifying stent-placing decisions for cases with low or no clinical ambiguity. Despite this disincentive, counterintuitively, a more revenue-driven physician can be *more* inclined to perform the advanced test. Finally, under an intermediate conflict-of-interest level, the physician may either perform the advanced test for all cases meriting consideration for PCI or never perform it, depending on the relative magnitude of (1) the risk associated with the advanced test and (2) the reimbursement rate for it.

Drawn from these results, we weigh three strategies intended to tackle overstenting:

i. Reducing the risk associated with the advanced test. We find that, although lowering its risk induces a higher uptake of the advanced test, it may not always benefit patients: under a high risk level, a moderate reduction in its risk may, surprisingly, *worsen* patient welfare. The intuition is a moderate risk reduction triggers a disproportional increase in the use of the advanced test.

ii. Providing a bonus for performing the advanced test. Under a low risk level, providing this bonus reduces overstenting and improves patient welfare. Using parameter values based on the U.S. interventional cardiology practice, we numerically evaluate the impact of offering this bonus on reducing overstenting and improving patient welfare.

iii. Implementing a bundled-payment scheme. We analyze a situation in which the physician is compensated using a bundled payment scheme. We show that such a payment scheme can, in a counterproductive way, discourage the physician from performing the advanced test.

1.1. Literature

Our paper touches on three strands of literature: operations management (OM), health economics, and interventional cardiology. We now position our research in the first two strands and discuss the relevant medical studies in the next section.

Several papers (Wang et al. 2010, Anand et al. 2011, Alizamir et al. 2013, Dai et al. 2017, Kim et al. 2019) in the OM literature address a service provider's diagnostic service (or similar in spirit) decisions and how these decisions affect service quality and efficiency. These papers contend that providing longer services might improve diagnostic accuracy and focus on the tradeoff between diagnostic accuracy and congestion externality; in other words, the service provider would always benefit from additional information in the absence of congestion externality. By contrast, we do not model congestion externality based on our observations that, in the interventional cardiology setting, (1) the incremental duration of PCI or an advanced intracoronary test is relatively brief compared with the combination of the preprocedure preparation time, clean-up time, and room turnover time, and (2) the block duration for cardiac catheterization is largely fixed, meaning physicians cannot increase system throughput by speeding up a case; thus, the queueing consideration does not play a meaningful role in physicians' decision making. Nevertheless, we reveal the existence of a disincentive for the service provider to obtain better information.

Our paper is somewhat related to studies of gatekeepers in the service operations literature. Shumsky and Pinker (2003) model a two-level service system in which the first level serves as a gatekeeper for the second level (a specialist). The gatekeeper is imperfectly capable of treating complex cases and may refer them to the specialist. Deo et al. (2020) study a two-level service system in which the gatekeeper is less than fully qualified, requiring an incentive scheme to motivate their referral decisions. Freeman et al. (2017) empirically investigate how the workload plays a role in influencing gatekeeper-providers' decisions about referring customers to specialists. Saghafian et al. (2018) consider a two-level service system in which the lower-level server can refer customers to a more knowledgeable upper-level server; the servers are not perfectly knowledgeable, such that the accuracy of their judgment depends on their skill levels. Different from our paper, however, their situation does not involve cases in which the correct decision is unknown by nature. By contrast, we explicitly assume a positive fraction of cases exists for which the correct decision is unknown. In addition, we model both the financial incentive and customer (patient) welfare. In a cardiac cath laboratory setting, the diagnostic process may also be viewed as a two-level system (angiography and advanced intracoronary testing) in which the first level is associated with more ambiguity in guiding diagnosis than the second level, but the same specialist conducts both levels, implying a very different incentive problem from those in the literature.

The OM community shows a growing interest in studying an expert's service decisions with strategic customers. For example, Paç and Veeraraghavan (2015) analyze a service provider's pricing and diagnosis strategies and consumers' procurement decisions in a strategic queueing context. Savva et al. (2019) study how local monopolists respond to customers' strategic queue-joining decisions and a yardstick-competition scheme, under which a monopolist service provider's reimbursement is determined by comparing its service performance with its peer local monopolists. Our paper departs from this literature in the following aspects. First, this literature assumes the expert can always correctly and costlessly diagnose each customer's type. In our paper, however, each customer's true condition cannot be perfectly observed or verified. Second, this literature assumes the service provider is solely concerned about his/her own financial interests. By contrast, we explicitly model the provider's social preference. That is, the service provider's utility is derived from both service revenue and customer utility. Third, the literature assumes consumers are strategic, whereas in our paper, patients are not strategic, because in a cardiac cath laboratory setting, patients typically defer to the physician in choosing between different courses of diagnosis and treatment.[4]

Our paper is connected to the OM community's ongoing efforts to understand "competing interests" in healthcare, that is, "secondary nonclinical objectives that can potentially influence how healthcare is delivered, evaluated, and reported" (Goh 2018, p. 51). Such attempts include, to name a few, the work by Adida et al. (2017), Ata et al. (2013), Bastani et al. (2016), Dai et al. (2017), Dai and Singh (2020), Delana et al. (2021), Kim et al. (2019), and Paç and Veeraraghavan (2015) (see Dai and Tayur 2020 for a comprehensive review of this stream of literature). From a practical perspective, inferring appropriateness of PCI decisions from patient outcome is medically difficult. In addition, patient outcome in this setting is exceedingly difficult to verify and hard to be contracted. For this reason, fee-for-service remains the dominant reimbursement model, whereas outcome-based reimbursement is rarely discussed in interventional cardiology. Consistent with the practice, we focus on a fee-for-service model in our analysis. Our paper contributes to this literature on *competing interests* by studying a specialist-care problem with *residual ambiguity* and highlighting the central importance of endogeneity in diagnostic testing decisions.

Our paper builds on the health economics literature on physicians' conflict-of-interest level, which contends that a physician may be neither purely profit driven nor purely patient centric; rather, this literature models a physician as having a mixed incentive. Arrow (1963) proposes the notion of *physician altruism* as a departure from the traditional profit-maximization framework in the economics literature. Ellis and McGuire (1986), in another milestone paper, model a physician's utility as a weighted combination of both a physician's own financial interest and patient welfare. They propose a prospective payment scheme that depends on the practice environment, including the physician's level of altruism. We follow the standard assumption from the above health economics literature that physicians have perfect knowledge of their own level of altruism and this level of altruism is known information. By incorporating clinical ambiguity, our paper generates results quite different from those in this literature. For example, we show that with the option to perform the advanced test, PCI use may be nonmonotonic in the conflict-of-interest level.

The physician decision-making process in our paper is related to the literature on exploitation versus exploration. McCardle (1985), for example, models a firm's costly information-acquisition process before adopting a new technology as an optimal stopping problem. More information reduces the firm's uncertainty about the profitability of the technology, yet the cost of information acquisition accumulates over time. By extension, *learning and earning* has been extensively studied in the operations management literature (Harrison et al. 2012, den Boer and Zwart 2014), building on the seminal work by Rothschild (1974) and Easley and Kiefer (1988), among others. One key difference between ours and the models in this literature is that even when information acquisition is costless, the decision maker in our setup may still not have an incentive to acquire additional, better information. The difference leads to distinctive managerial implications.

The rest of the paper is organized as follows. In the next section, we present a brief background on interventional cardiology. In Section 3, we present our modeling framework. Section 4 analyzes the physician's decision on the advanced intracoronary test. Section 5 presents managerial implications. Section 6 considers a case in which the physician uses privately observed patient characteristics in making decisions. We conclude in Section 7. All technical proofs appear in the online appendix.

2. Background on Interventional Cardiology

We now provide an overview of interventional cardiology decision-making in the United States, focusing on the issues most relevant to this study.

Despite great strides over the past several decades, cardiovascular disease remains the most common cause of death in the United States, and coronary artery disease (CAD) is the major underlying culprit. For patients with acute coronary syndromes, the benefit of PCI is unequivocal (Mehta et al. 2005, Patel et al. 2009). For patients with stable CAD, on the other hand, management is more nuanced (Patel et al. 2012). Whereas large randomized trials have shown stable angina patients receive significant quality-of-life benefits from PCI (Weintraub et al. 2008), PCI performed on a lesion that does not cause ischemia is not beneficial and may cause harm (Patel et al. 2012).

Patients with stable CAD are generally evaluated first in a cardiologist's office with noninvasive stress testing. If the stress test result is negative or interpreted to be low risk and if the patient has only mild angina, pharmacologic therapy is attempted. However, if the stress test result is interpreted to be high risk or if the patient develops worsening angina despite aggressive pharmacologic therapy, a referral for cardiac catheterization is made. Our model focuses on the decision process starting with cardiac catheterization.

Cardiac catheterization has traditionally been held as the definitive diagnostic procedure for CAD; part of the procedure involves generating angiograms showing blockages or narrowings in arteries. Figure 1 provides an example of the procedure with an angiogram displayed on the lower screens. An angiographic 70% diameter stenosis is traditionally considered the threshold at which PCI would be reasonable. However, visual interpretation of angiograms is highly subjective, and considerable interobserver and even intraobserver variability has long been known to exist for stenoses of intermediate severity (Topol and Nissen 1995).

Figure 1. (Color online) Cardiac Cath Laboratory in a Major Maryland Hospital

Irregularly shaped plaque within the coronary lumen and diffuse disease with a lack of an obvious normal reference coronary segment complicate determination of the true extent of a stenosis (Topol and Nissen 1995). Therefore, even for patients who have undergone cardiac catheterization, uncertainty about the significance of a lesion often comes into play.

More advanced intracoronary testing modalities have been developed to help guide clinical decision making. In particular, fractional flow reserve (FFR) measurement has gained prominence as an adjunct to coronary angiography to aid in the determination of a physiologically relevant stenosis (Tonino et al. 2009, De Bruyne et al. 2012). In this procedure, intracoronary blood pressures are simultaneously measured downstream and upstream of a stenosis during a period of maximum pharmacologically induced hyperemia. P_a (upstream intracoronary blood pressure) and P_d (downstream intracoronary blood pressure) are measured simultaneously, and FFR is calculated using $FFR = P_d/P_a$ (Pijls et al. 1995) (see Figure 2 for an illustration of the FFR test). Physiologically important stenoses should cause a significant impediment in flow and thus a drop in the blood pressure downstream from the stenosis. Indeed, recent trials have shown improved patient outcomes when PCI is performed on lesions with an FFR of less than 0.75 to 0.80, although a gray zone of indeterminate benefit has also been described (Petraco et al. 2013, Johnson et al. 2014). As a result, the tendency for physicians to use FFR to help guide PCI in stable CAD patients has been growing, although overall uptake remains physician dependent. Practice guidelines support this trend, calling the use of FFR "reasonable to assess angiographic intermediate coronary lesions" (Class IIa recommendation) with a robust level of clinical evidence (Lotfi et al. 2014, p. 510).

3. Model

We consider the encounter between a physician and a stable angina patient in a cardiac cath laboratory. We do not consider acute cases such as one in which a patient experiences a heart attack, because in these cases, the benefits of PCI are well established (Keeley et al. 2003, Chan et al. 2011). We focus on patients who receive optimal antianginal therapy and require a cardiac catheterization procedure; we do not consider cases well established as unsuitable for PCIs, such as those with multivessel disease requiring coronary artery bypass grafting (CABG). The physician conducts the fluoroscopy-guided cardiac catheterization procedure, which generates an angiogram that can be used to assess the narrowing of a patient's coronary arteries. The physician subsequently makes treatment decisions based on the angiogram and on patient-specific information such as demographics, medical history, and patient presentation. We control patient-specific information and study the physician's decision-making process for a patient of any given category. We focus on a one-shot patient-physician interaction while abstracting away from possible follow-ups, because, in practice, most interventional cardiologists in the United States make diagnostic and treatment decisions based solely on the information from the current patient visit, and a vast majority of patients visit the cardiac cath laboratory only once. For example, at one large hospital at which a coauthor of this paper is an interventional cardiologist, according to the CathPCI registry, for 2014–2015, staged procedures (i.e., more than one visit required) account for only 9.6% of all the procedures.

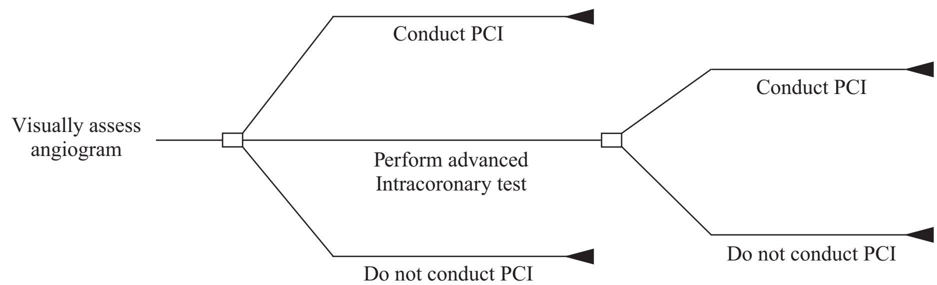
Figure 2. (Color online) Monitor Screen Showing the Result of an FFR Test

In practice, the physician may also perform an optional advanced test (e.g., FFR) after visually assessing a patient's lesion severity from the angiogram. If the physician decides not to perform an advanced test, the physician will base the PCI decision on the reading of the angiogram. If the physician chooses to perform the advanced test, the test is used to guide the PCI decision. In Figure 3, we use a decision tree to illustrate the physician's decision-making process in a cath laboratory. We label each pathway to make it convenient to discuss bundled-payment schemes later in Section 5.4.

3.1. Modeling Angiogram-Based Decision Making

3.1.1. Patient Welfare. As explained in the preceding section, patients with stable CAD do not always benefit from PCI procedures, and inappropriate PCI procedures may cause health hazards. We denote by s the patient's true state, which may be A (appropriate for a PCI procedure), U (uncertain), or I (inappropriate for a PCI procedure). Without loss of generality, in the case of $s = I$, we normalize patient utility to zero if the patient does not receive a PCI procedure and remains on optimal therapy. We denote by b the patient's benefit from an appropriate PCI procedure, h the patient's potential harm from an inappropriately performed procedure, and l the patient's welfare loss for not

Figure 3. Decision Tree for Interventional Cardiology Decision Making



Notes. (a) Low risk-to-reimbursement ratio. (b) High risk-to-reimbursement ratio.

receiving an appropriate procedure. In practice, the values of these parameters may depend on patient characteristics, but in a cardiologist's mental accounting system, patients may be roughly classified into a number of types within each of which the values are roughly the same. We choose to focus on modeling patients of the same type and handled with the same decision rule; our key results extend to the case in which the physician may possess unobservable private information specific to each patient. Without loss of generality and for ease of analysis, for an uncertain case, we normalize the patient's payoff when receiving a PCI procedure (denoted by x) to zero and do the same for the patient's payoff when not receiving a PCI procedure (denoted by y), meaning patients belonging to uncertain cases gain neither benefit nor harm from PCI procedures. Table 1 summarizes patient payoff from the PCI decision.

Let θ denote the visually assessed angiographic stenosis (i.e., the level of narrowing of coronary arteries as from visually examining the angiogram). We normalize the support of θ to [0,1] without loss of generality: $\theta = 0$ corresponds to the case with the minimal level of narrowing that merits the possibility of a PCI procedure, and $\theta = 1$ corresponds to the case with the maximum narrowing level suitable for PCIs.[5] The distribution of the physician's visually assessed angiographic stenosis, denoted by $f(\theta|s)$, is conditional on s. We assume $f(\theta|s) > 0$ for all $0 < \theta < 1$ and has monotone likelihood ratios; that is, $f(\theta|A)/f(\theta|U), f(\theta|U)/f(\theta|I)$, and $f(\theta|A)/f(\theta/I)$ increase in θ. In other words, a higher θ is more indicative of PCI appropriateness. We define two functions of the physician's visually assessed angiographic stenosis (θ): (1) $\alpha(\theta)$: the likelihood that a PCI procedure is appropriate, which, by Bayes' law, is $\alpha(\theta) = \frac{f(\theta|A)\xi_A}{f(\theta|A)\xi_A + f(\theta|I)\xi_I + f(\theta|U)\xi_U}$, where $\xi_s, s \in \{A, U, I\}$ denotes the prior probability that the patient's true state is s; (2) $\beta(\theta)$: the likelihood that a PCI procedure is inappropriate can be represented as $\beta(\theta) = \frac{f(\theta|I)\xi_I}{f(\theta|A)\xi_A + f(\theta|I)\xi_I + f(\theta|U)\xi_U}$. Thus, given θ, the likelihood that a PCI procedure is neither appropriate nor inappropriate is $1 - \alpha(\theta) - \beta(\theta)$. In particular, $\alpha(0) = 0$, $\beta(0) = 1$, $\alpha(1) = 1$, and $\beta(1) = 0$. In addition, $\alpha(\theta) + \beta(\theta) < 1$ for $0 < \theta < 1$; that is, unless the visually assessed angiographic stenosis θ is 0 or 1, with a positive likelihood $1 - \alpha(\theta) - \beta(\theta)$, a PCI is neither appropriate nor inappropriate. Such a likelihood captures the *clinical ambiguity* of a case.

Table 1. Patient Payoff from PCI Decision

True state	PCI is conducted	PCI is not conducted
$s = A$ (appropriate)	b	$-l$
$s = U$ (uncertain)	x	y
$s = I$ (inappropriate)	$-h$	0

Consistent with clinical practice, the monotone likelihood ratios give the property that $\alpha(\theta)$ increases in θ and $\beta(\theta)$ decreases in θ. Using this framework, given θ, the expected patient welfare is $b\alpha(\theta) - h\beta(\theta)$ if a PCI procedure is conducted, and $-l\alpha(\theta)$ otherwise. We assume away patients' out-of-pocket expenses, which may be modeled as, equivalently, a decrease in the net benefit (b) from an appropriate PCI procedure and an increase in the harm (h) from an inappropriate one; this consideration has a moderating effect and our findings are directionally valid.

3.1.2. Physician Utility. The physician benefits financially from collecting reimbursement for conducting PCI procedures. We denote by r_p the revenue collected from a case in which a PCI procedure is conducted and denote by r_d the revenue collected from a case in which only diagnostic angiography is conducted. In current U.S. medical practice, the reimbursement rate for a case with a PCI procedure is significantly higher than for a case with diagnosis only; that is, $r_p > r_d$.

Consistent with the literature on expert service (Durbin and Iyer 2009) and physician utility (Léger 2008, Godager and Wiesen 2013), we assume the physician values both financial gains and patient well-being. We use $\phi \in [0,1]$ to capture the weight of financial gains in the physician's mental-accounting system, and use $(1-\phi)$ to capture the weight of patient welfare. Our model does not explicitly capture the long-term reputation or legal implications of PCI overuse by a physician, and we expect such implications would be likely to dampen the parameter ϕ. A larger ϕ indicates a higher conflict-of-interest level: $\phi = 0$ corresponds to the case in which the physician is fully altruistic, whereas $\phi = 1$ corresponds to the case in which the physician is fully driven by financial gains. Additionally, in Section 6, we account for unobservable factors in physician decision making.

We do not explicitly model the cost of tests and procedures, because in the practice of interventional cardiology, the cost of providing the tests and procedures is largely fixed and the marginal cost is comparatively low. One way to incorporate the marginal cost is to slightly reduce the per-procedure revenue; we expect all our findings to hold directionally.

3.1.3. Physician Decision. Whereas the decision analysis literature often models ambiguity by using decision rules such as minimax or minimax regret (Manski 2010), a commonly adopted approach in the health economics literature entails the expected utility criterion but allows the decision makers to have different attitudes toward ambiguity. Driven by empirical findings that physicians are ambiguity averse (Curley et al. 1989, Han et al. 2009, Portnoy et al. 2013), we assume the physician forms a low-valued belief that the sum of the likelihoods of the two possible events (PCI is appropriate, and PCI is inappropriate) is less than one, treating the imprecise scenarios (with probability $1-\alpha(\theta)-\beta(\theta)$ in our case) as if they do not exist (Arad and Gayer 2012). Given θ, the visually assessed angiographic stenosis, the physician's utility from conducting a PCI procedure can be represented as $\mu_P(\theta) = \phi r_p + (1-\phi)\left[b\alpha(\theta) - h\beta(\theta)\right]$, whereas the physician's utility from providing diagnostic service but not conducting PCI can be represented as $\mu_{NP}(\theta) = \phi r_d + (1-\phi)[-l\alpha(\theta)]$. For conciseness of presentation, we define a critical value of ϕ as $\phi^{(0)} = h/(h + r_p - r_d)$, which increases in the ratio of the harm from an inappropriate PCI procedure (captured by h) to the additional revenue collected from conducting a PCI procedure (captured by $r_p - r_d$). The following lemma presents the physician's optimal angiogram-guided decision threshold.

Lemma 1. *When guided by an angiogram, the physician conducts a PCI procedure if and only if the visually assessed angiographic stenosis θ is no smaller than a stenosis threshold $\overline{\theta}^*$, which is specified here:*

i. *If $0 \le \phi < \phi^{(0)}$, the optimal stenosis threshold $\overline{\theta}^* > 0$ uniquely solves $h \cdot \beta(\overline{\theta}) - (b+l)\cdot\alpha(\overline{\theta}) = \phi(r_p - r_d)/(1-\phi)$.*

ii. *If $\phi^{(0)} \le \phi \le 1$, $\overline{\theta}^* = 0$.*

This threshold policy is consistent with interventional cardiology practice. Furthermore, this lemma implies the optimal stenosis threshold $\overline{\theta}^*$ depends on ϕ. The threshold $\overline{\theta}^*$ is constant at zero if ϕ is no lower than $\phi^{(0)}$, meaning $\phi^{(0)}$ is the conflict-of-interest threshold above which the physician conducts PCI procedures for all cases meriting consideration for placing stents. To highlight this effect, in the rest of the paper, we write the optimal stenosis threshold $\overline{\theta}^*$ as a function of ϕ.

When $\phi = 0$, that is, when the physician is fully altruistic, we have from Lemma 1 that the physician's stenosis threshold $\overline{\theta}(0)$ satisfies $\frac{\alpha(\overline{\theta}^*(0))}{\beta(\overline{\theta}^*(0))} = \frac{h}{b+l}$. As ϕ increases, Lemma 1 suggests $\overline{\theta}^*(\phi)$ (weakly) decreases, consistent with the intuition that a higher conflict-of-interest level drives more use of PCI procedures.

3.2. Modeling Advanced Intracoronary Test

We now present our model of the advanced intracoronary test, which is primarily motivated by FFR—the gold standard for assessing the physiologic severity of coronary stenosis (Taylor et al. 2013) that "almost seems too good to be true," according to Dr. William Fearon (Fornell 2013) of Stanford University—but may extend to other advanced tests such as intravascular ultrasound (IVUS) and optical coherence tomography (OCT).

Despite their informational value, advanced intracoronary tests such as FFR (De Bruyne et al. 2012) may introduce health risks to patients. Such risks include wire dissection, perforation, transient bradycardia, coronary spasm, and ventricular arrhythmias (Topol 2008). We denote by E the expected risk to which the advanced test exposes a patient.

We assume $h > \epsilon$ based on our observation from the interventional cardiology practice. In addition, we assume the reimbursement rate for the advanced test, denoted by r_a, is insufficient to cover the loss of revenue from a PCI procedure that the advanced test rules out; that is, $(r_p - r_d) > r_a$.

Let η denote the output of the advanced test, with a support of $[0, 1]$. In the case of an FFR test, η corresponds to the outcome of the test, which is a lesion-specific index defined as the ratio of maximum flow through a stenotic lesion to the maximum normal flow of the same vessel. A smaller value of η indicates a more severe stenosis. The value of η is automatically generated by the test, essentially removing the subjectivity associated with the visual assessment of angiograms. If $\eta \in [0, \eta^n]$, a PCI procedure is deemed appropriate; if $\eta \in (\eta^u, 1]$, a PCI procedure is deemed inappropriate. We assume $\eta^n < \eta^u$ to be consistent with the latest medical findings that a grey zone associated with the FFR threshold exists (Petraco et al. 2013, Johnson et al. 2014) in which conducting a PCI is neither appropriate nor inappropriate; from our assumption in Section 3.1.1, the patient's payoff (x if a PCI procedure is conducted, and y otherwise) in this case is zero.

The physician is required to generate and visually assess the angiogram before deciding whether to perform the advanced test. Formally, given the visual assessment θ, the output of the advanced test $\eta \in [0, 1]$ follows a conditional probability distribution $G(\eta|\theta)$ with a density $g(\eta|\theta)$. Using the definitions of $\alpha(\cdot)$ and $\beta(\cdot)$, we have the following relationships between $G(\cdot|\theta)$, $\alpha(\cdot)$, and $\beta(\cdot)$:

$$G(\eta^n|\theta) = \alpha(\theta) \text{ and } 1 - G(\eta^u|\theta) = \beta(\theta). \quad (1)$$

Thus, given the visual assessment θ, $G(\eta^u) - G(\eta^n) = 1 - \alpha(\theta) - \beta(\theta)$. In other words, clinical ambiguity may also be interpreted as the likelihood that a case falls into the grey zone according to the advanced test.

4. Analysis

We now analyze the physician's diagnostic and treatment decision making with the option of performing the advanced test. Table 2 summarizes the notation used in the rest of the paper.

We can show that a threshold policy characterizes the physician's advanced test–guided PCI decision; that is, a threshold $\overline{\eta}$ exists such that a PCI procedure is conducted if and only if the output of the advanced test η is no larger than $\overline{\eta}$. Because η is a machine-generated output and can be used as verifiable evidence in court, the physician would always choose $\overline{\eta} \le \eta^u$. Indeed, we can show the optimal threshold is η^u.

We examine the physician's decision regarding whether to perform the advanced test. Using (1), we represent the physician's expected utility from performing the advanced test for given θ as

$$\mu_a(\theta) = \phi \cdot \{(r_p - r_d)[1 - \beta(\theta)] + r_d + r_a\} + (1 - \phi) \cdot [b \cdot \alpha(\theta) - \epsilon]. \quad (2)$$

In this equation, the first part of its right-hand side represents the physician's utility from the revenue that includes the fees for performing the advanced test (r_a), for performing the diagnosis (r_d), and for conducting a PCI procedure (r_p) with the probability of $1 - \beta(\theta)$. The second part of its right-hand side represents the physician's utility from patient welfare, which includes the expected benefit from an appropriate PCI procedure ($b \cdot \alpha(\theta)$) minus the additional procedural risk (E) from performing the advanced test. If, however, the physician decides not to perform the advanced test, we know from Lemma 1 that, given θ, the physician's expected utility is

$$1(\theta \ge \overline{\theta}^*(\phi)) \cdot \{\phi \cdot r_p + (1 - \phi)[b \cdot \alpha(\theta) - h \cdot \beta(\theta)]\} + 1(\theta < \overline{\theta}^*(\phi)) \cdot [\phi \cdot r_d - (1 - \phi) \cdot l \cdot \alpha(\theta)]. \quad (3)$$

Comparing (2) with (3) yields the condition for the physician to perform the advanced test.

Table 2. Notation

Notation	Definition
θ	Visually assessed angiographic stenosis
S	A patient's true state; $s \in \{A, U, I\}$
ϕ	Conflict-of-interest level
$\alpha(\theta)$	Likelihood that a PCI procedure is appropriate Given a visually assessed angiographic stenosis of θ
$\beta(\theta)$	Likelihood that a PCI procedure is inappropriate Given a visually assessed angiographic stenosis of θ
b	Patient's benefit from an appropriate PCI procedure
h	Patient's potential harm from an inappropriate PCI procedure
l	Patient's welfare loss for not receiving an appropriate PCI procedure
x	Patient's payoff from a PCI procedure when the patient's true state is uncertain
y	Oatient's payoff from not conducting a PCI procedure when the patient's true State is uncertain
E	Expected risk to which the advanced test exposes a patient
η	Output of the advanced test
η^n	Maximum value of η for a PCI procedure to be considered as appropriate
η^u	Minimum value of η for a PCI procedure to be considered as inappropriate
r_p	Revenue collected from a case in which a PCI procedure is conducted
r_d	Revenue collected from a case in which only diagnostic angiography is conducted
r_a	Revenue collected from performing the advanced test
$\phi^{(0)}$	Critical value in the conflict-of-interest level above which an angiogram-guided physician conducts PCI procedures for all cases meriting consideration for placing stents
$\phi^{(1)}, \phi^{(2)}$	Critical values used in determining whether the conflict-of-interest level is low, medium, or high
τ	Proportion of angiogram-guided PCI decisions that the hospital chooses to verify with the advanced test
λ	Penalty imposed for each PCI procedure deemed inappropriate from a randomly enforced advanced test

Lemma 2. *If $\theta < \overline{\theta}^*(\phi)$, the physician performs the advanced test if and only if θ satisfies*

$$(1 - \phi)(b + l)\alpha(\theta) - \phi(r_p - r_d)\beta(\theta) \ge (1 - \phi)\epsilon - \phi(r_a + r_p - r_d). \quad (4)$$

If $\theta \ge \overline{\theta}^*(\phi)$, the physician performs the advanced test if and only if θ satisfies

$$[(1 - \phi)h - \phi(r_p - r_d)]\beta(\theta) \ge (1 - \phi)\epsilon - \phi r_a. \quad (5)$$

In the first case of Lemma 2, the physician would not perform PCI when guided solely by the angiogram, because the visually assessed angiographic stenosis θ is below the stenosis threshold $\overline{\theta}^*(\phi)$. In this case, (4) means the physician will perform the advanced test if the physician may benefit from PCI procedures—including both patient benefit (captured by $b + l$) and increased revenue (captured by $r_p - r_d$)—that would have been missed without the advanced test. In the second case, the physician would perform PCI when guided solely by the angiogram, because $\theta \geq \overline{\theta}^*(\phi)$. (5) suggests the physician will perform the advanced test if the harm to patients (h) from a potentially inappropriate PCI procedure, combined with the additional revenue (r_a), significantly outweighs the potential revenue loss ($r_p - r_d$) and the additional risk (E).

Lemma 2 suggests the physician faces a four-way tradeoff in deciding whether to perform the advanced test: (i) patient welfare improvement from the advanced test, which may result from reduced patient harm if the advanced test rules out a PCI procedure that would otherwise have been recommended, or increased patient benefit if the advanced test recommends a PCI procedure that would otherwise have been missed; (ii) additional risk introduced by the advanced test; (iii) potential revenue loss or increase from PCI procedures due to the advanced test; and (iv) additional revenue from the advanced test. The relative importance of these considerations varies according to the conflict-of-interest level (ϕ): When ϕ is close to zero, the tradeoff is largely between the first two considerations. As ϕ increases, the last two considerations gain importance. As we demonstrate in Propositions 1–3, the dynamics among these tradeoffs yield compelling insights into the physician's decisions regarding the advanced test.

For conciseness of presentation, we define two critical values of ϕ: $\phi^{(1)} = \frac{\epsilon}{\epsilon + r_a}$ and $\phi^{(2)} = \frac{h-\epsilon}{h-\epsilon+r_p-r_d-r_a}$.

The first threshold $\phi^{(1)}$ is determined by the relative magnitude of the risk (ϵ) that the advanced test introduces with respect to the service fee collected from the test (r_a). The second threshold $\phi^{(2)}$ is determined by the relative clinical benefit of the advanced test ($h - \epsilon$) with respect to the monetary loss ($r_p - r_d - r_a$) when the advanced test helps rule out an inappropriate PCI procedure. The following lemma compares $\phi^{(1)}$ with $\phi^{(2)}$.

Lemma 3. *The relationship* $\phi^{(1)} \geq \phi^{(2)}$ *holds if and only if* $\epsilon / r_a \geq h/(r_p - r_d)$.

This lemma suggests $\phi^{(1)}$ is larger than $\phi^{(2)}$ when the risk-to-reimbursement ratio of the advanced test (ϵ / r_a) is sufficiently high, and vice versa.

We loosely categorize a physician's conflict-of-interest level in the following fashion: We refer to the physician's conflict-of-interest level as *low* if $\phi < \min\{\phi^{(1)}, \phi^{(2)}\}$, *intermediate* if $\min\{\phi^{(1)}, \phi^{(2)}\} \leq \phi \leq \max\{\phi^{(1)}, \phi^{(2)}\}$, and *high* if $\phi > \max\{\phi^{(1)}, \phi^{(2)}\}$. This categorization has structural implications for the physician's testing patterns, as elucidated in our characterization of the physician's key tradeoff and testing policy under various ranges of ϕ; see Table 3 for a preview of these results. For ease of presentation, we define a function $z(\cdot)$

$$z(\phi) = \frac{(1-\phi)\epsilon - \phi r_a}{(1-\phi)h - \phi(r_p - r_d)}.$$

Table 3. Summary of Physician's Advanced Testing Decision

Range of ϕ	Key tradeoff	Perform the advanced test for
Low	(i) Patient welfare improvement vs. (ii) risk of the test	$\theta^{(1)} \leq \theta \leq \beta^{(-1)}(z(\phi))$.
Medium	(ii) Risk of the test vs. (iii) reimbursement from the test	All cases if $\epsilon/r_a \leq h/(r_p - r_d)$; No cases if $\epsilon/r_a > h/(r_p - r_d)$.
High	(iii) Reimbursement from the test vs. (iv) reimbursement from PCI procedures	$\theta \geq \beta^{-1}(z(\phi))$.

4.1. Low Conflict-of-Interest Level ($\phi < min\{\phi^{(1)}, \phi^{(2)}\}$)

Consider a physician with a low conflict-of-interest level (characterized by $\phi < \min\{\phi^{(1)}, \phi^{(2)}\}$). In the rest of the paper, we assume $\beta^{(-1)}(z(\phi)) \geq \overline{\theta}^*(\phi)$ to focus on the interesting case in which the physician will perform the advanced test for some patients.

Proposition 1. *When* $\phi < \min\{\phi^{(1)}, \phi^{(2)}\}$, *the physician performs the advanced test if and only if* $\theta^{(1)} \leq \theta \leq \beta^{(-1)}(z(\phi))$, *where* $\theta^{(1)}$ *satisfies* $\phi(r_p - r_d)[1 - \beta(\theta)] + (1-\phi)(b+l)\alpha(\theta) = (1-\phi)\epsilon - \phi r_a$ *at* $\theta = \theta^{(1)}$, *and is no larger than* $\overline{\theta}^*(\phi)$.

Proposition 1 states that under a conflict-of-interest level, the physician performs the advanced test primarily for borderline cases. Specifically, the physician chooses to perform the advanced test only when the visual assessment of angiogram (θ) is close to $\overline{\theta}^*(\phi)$, that is, when θ either approaches $\overline{\theta}^*(\phi)$ from below, namely, $\theta^{(1)} \leq \theta \leq \overline{\theta}^*(\phi)$, or from above, namely, $\overline{\theta}^*(\phi) \leq \theta \leq \beta^{(-1)}(z(\phi))$. Stated differently, the advanced test is called for when the physician is most ambiguous about the PCI decision based solely on the angiogram. This result demonstrates that under a low conflict-of-interest level, the physician views the advanced test as a device to mitigate the clinical ambiguity from angiogram-guided PCI decision making.

We have the following corollary from Proposition 1.

Corollary 1. *If* $\phi < \min\{\phi^{(1)}, \phi^{(2)}\}$, *the physician does not perform the advanced test when* $\theta = 0$ *or* $\theta = 1$.

Corollary 1 states that when the conflict-of-interest level is low, the advanced test is not performed in the absence of clinical ambiguity. This result is aligned with our finding that a physician with a low conflict-of-interest level performs the advanced test chiefly to mitigate clinical ambiguity.

4.2. Intermediate Conflict-of-Interest Level ($min\{\phi^{(1)}, \phi^{(2)}\} \le \phi \le max\{\phi^{(1)}, \phi^{(2)}\}$)

Next, we examine the case in which the conflict-of-interest level is intermediate; that is, $\min\{\phi^{(1)},\phi^{(2)}\} \le \phi < \max\{\phi^{(1)},\phi^{(2)}\}$. The following proposition characterizes the physician's testing behavior under an intermediate conflict-of-interest level.

Proposition 2. *When* $\min\{\phi^{(1)},\phi^{(2)}\} \le \phi \le \max\{\phi^{(1)}, \phi^{(2)}\}$, *the physician performs the advanced test regardless of the value of* θ *if* $\epsilon/r_a \le h/(r_p - r_d)$, *or, equivalently,* $\phi^{(1)} \le \phi^{(2)}$; *the physician never performs the advanced test otherwise.*

Proposition 2 implies the risk-to-reimbursement ratio plays an important role in the four-way tradeoff when the conflict-of-interest level is intermediate: The physician either always performs the advanced test when the risk-to-reimbursement ratio is low (i.e., $\epsilon/r_a \le h/(r_p - r_d)$) or never performs the advanced test otherwise, regardless of the angiogram. Thus, decreasing the risk associated with the advanced test and increasing its reimbursement rate can have a drastic *behavior-inducing effect*: The physician may change from not performing the advanced test at all to performing it for all eligible cases. The intuition is as follows: Because the conflict-of-interest level is intermediate, the physician weighs revenue and patient welfare nearly equally, and thus the impact of the specific value of ϕ is not significant. The physician makes the testing decision by comparing its cost (testing risk ϵ and PCI revenue loss $(r_p - r_d)$) and its benefit (patients' reduced harm h and testing revenue r_a). Then, clearly, $\epsilon/r_a \le h/(r_p - r_d)$ implies the cost is lower than the benefit, and thus the physician performs the advanced test. Otherwise, the physician never performs the advanced test.

A recent study (Toth et al. 2014) shows 27% of interventional cardiologists have never performed advanced intracoronary tests to guide their PCI decision making. In practice, one might reasonably expect a considerable proportion of practitioners to be of intermediate conflict-of-interest levels. Our analysis shows increasing the reimbursement level for the advanced test or instituting educational programs is most effective when targeted at these physicians, inducing their behavior from never performing the tests to consistently following the medical guidelines supporting the use of advanced intracoronary tests.

We have the following corollary from Proposition 2.

Corollary 2 . *If* $\epsilon/r_a \le h/(r_p - r_d)$, $(\phi^{(2)} - \phi^{(1)})$ *increases in* r_a *and decreases in E.*

Note from Proposition 2 that because $\epsilon/r_a \le h/(r_p - r_d)$, $(\phi^{(2)} - \phi^{(1)})$ is the size of the continuum of the conflict-of-interest levels under which the physician performs the advanced test regardless of the visually assessed angiographic stenosis. From a healthcare leader's perspective, this corollary, together with Proposition 2, implies that when the risk of the advanced test is relatively low, providing a bonus for performing the advanced test may generate a behavior-inducing effect conducive to the reduction of overstenting. Later, in Section 5.3, we evaluate this option in detail.

4.3. High Conflict-of-Interest Level ($\phi > max\{\phi^{(1)}, \phi^{(2)}\}$)

As stated earlier, the physician is under a high conflict-of-interest level if $\phi \ge \max\{\phi^{(1)}, \phi^{(2)}\}$, in which case $\overline{\theta}^*(\phi) = 0$. Clearly, any advanced test may call into question the appropriateness of a PCI procedure the physician would otherwise have conducted. The following proposition presents the physician's diagnostic decision under a high conflict-of-interest level.

Proposition 3. *If* $\phi > \max\{\phi^{(1)}, \phi^{(2)}\}$, *the physician performs the advanced test if and only if* $\theta \ge \beta^{-1}(z(\phi))$.

Proposition 3 suggests that if the conflict-of-interest level is sufficiently high (i.e., $\phi > \max\{\phi^{(1)}, \phi^{(2)}\}$), the physician may still perform the advanced test, but only when the visually assessed angiographic stenosis θ is large enough, that is, $\theta \ge \beta^{-1}(z(\phi))$. To understand the result, notice that when θ is large enough, the probability that the advanced test would reverse the physician's initial angiogram-guided PCI decision is low. Thus, the likelihood that the advanced test would reverse a PCI decision is fairly low, and the revenue collected from performing the advanced test would compensate for the expected financial loss. On the other hand, if θ is not large enough, performing the advanced test has a high likelihood of reducing the physician's PCI revenue.

Proposition 3 gives the following corollary.

Corollary 3. *Below are two special cases of interest:*

i. *When* $\epsilon = 0$, *the physician does not always perform the advanced test.*

ii. *Under a high conflict-of-interest level (i.e.,* $\phi > \max\{\phi^{(1)}, \phi^{(2)}\}$*), the physician performs the advanced test at* $\theta = 1$.

Corollary 3(i) deals with a special case when $\epsilon = 0$ (i.e., the advanced test is risk free). In this case, despite the indisputable benefit of the advanced test, the physician still may not always perform it. This result clearly demonstrates a disincentive to perform the advanced test, which might prevent the physician from conducting PCI on patients who would have otherwise been qualified for PCI based solely on the angiogram.

As another special case, Corollary 3(ii) states when $\theta = 1$, at which point no clinical ambiguity exists, the physician still chooses to perform the advanced test under a very high conflict-of-interest level. In other words, the physician performs the advanced test when the probability is high that the advanced test would justify the angiogram-guided recommendations for PCI procedures.

Proposition 3 reveals the striking effect of a disincentive for performing the advanced test, as echoed by Fornell (2013): "Routine use [of FFR] may provide a financial disincentive, [because] the reimbursement decreases with less frequent stent implantation." Because of this financial disincentive, one might expect the physician to be less likely to perform the advanced test under a higher conflict-of-interest level. By contrast, the following proposition states the opposite may be true.

Proposition 4. *Under a high conflict-of-interest level (i.e., $\phi > \max\{\phi^{(1)}, \phi^{(2)}\}$), if $\epsilon/r_a \geq h/(r_p - r_d)$, as ϕ increases, the physician is more inclined to perform the advanced test; otherwise, as ϕ increases, the physician is less inclined to perform the advanced test.*

Proposition 4 states that under a higher conflict-of-interest level, the physician may be more inclined to perform the advanced test. This result is rather surprising given the aforementioned financial disincentive. Here, we provide some intuition behind the result. Under a high risk-to-reimbursement ratio of the advanced test (i.e., $\epsilon/r_a \geq h/(r_p - r_d)$), when $\phi^{(0)} \leq \phi \leq \phi^{(1)}$, the physician would not perform the advanced test, because its risk is relatively high. When $\phi \geq \phi^{(1)}$, as ϕ increases further from $\phi^{(1)}$, the physician is less concerned about patient welfare. With an increased focus on the additional revenue and a decreased focus on the procedural risk (which is high in this case), the physician is more inclined to perform the advanced test. The potential loss of PCI revenue is not significant, because the physician performs the advanced test in a small region covering patients with high values of visually assessed angiographic stenosis.

On the other hand, under a low risk-to-reimbursement ratio of the advanced test (i.e., $\epsilon/r_a < h/(r_p - r_d)$), when $\phi^{(0)} \leq \phi \leq \phi^{(2)}$, the physician always performs the advanced test, because of the substantial informational benefit of the test. As ϕ increases further from $\phi^{(2)}$, the physician is less concerned about expected patient welfare but more concerned about the potential loss of PCI revenue because of performing the advanced test (which is nontrivial because the testing region covers patients corresponding to a wide range of θ) and is thus less likely to perform it.

5. Practical Implications for Tackling Overstenting

Despite the consensus that PCI procedures are being significantly overused (Huang and Rosenthal 2015), a paucity of analytical insights into various strategies for tackling overstenting exists, with the advanced test being an important lever. To fill this gap, we use our modeling framework to generate implications for improving the interventional cardiology practice (Section 5.1) and analyze various options for reducing overstenting, which include reducing the risk of the advanced test (Section 5.2), providing a bonus for performing the advanced test (Section 5.3), and implementing a bundled payment scheme (Section 5.4).

5.1. Structural Patterns for Performing the Advanced Test

We numerically estimate the parameters of our model and use the result to illustrate how the recommendations from our model differ from clinical decisions made on the ground.

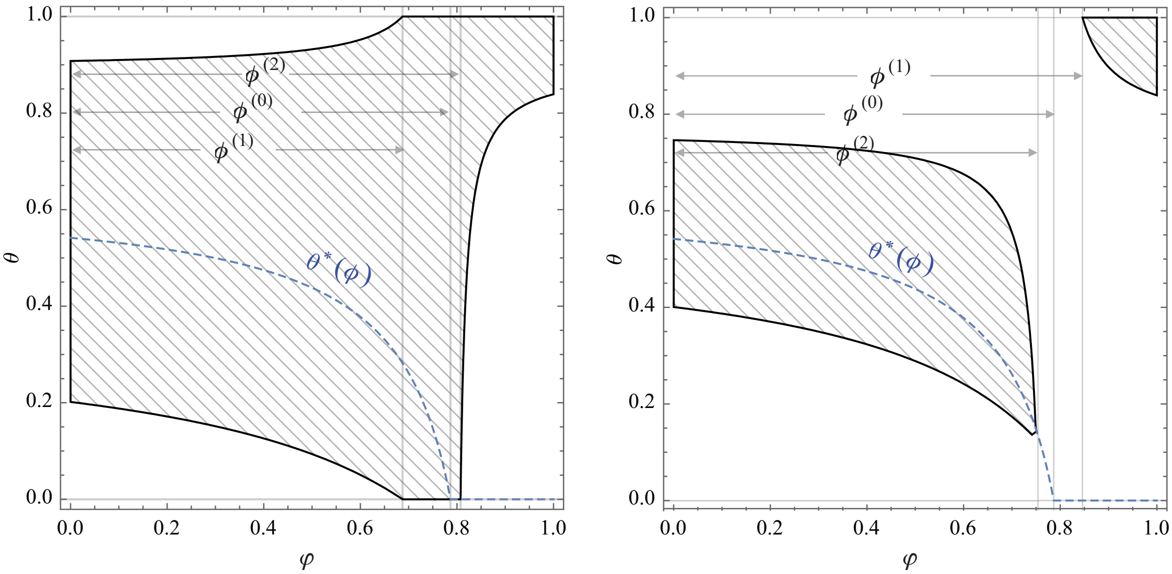
For the cost and reimbursement parameters, we draw from the U.S. interventional cardiology practice; for clinical parameters, we estimate these values based on Biasco et al. (2015) (see online appendix for details).

We use $r_d = \$267, r_p = \$623$, and $r_a = \$91$ based on the prevailing Medicare physician reimbursement rates (Boston Scientific 2014). In addition, we estimate that $b = \$2{,}542$, $h = \$1{,}312$, and $l = \$162.3$ (see online appendix for details of estimating b and h). We use two values of E: a low risk of \$200 and a high risk of \$500, which correspond to the cases in which the risk-to-reimbursement ratios of the advanced test are referred to as low and high, respectively.

We consider the following family of functions of $\alpha(\theta; s, t)$ and $\beta(\theta; s, t)$, where $s, t > 0$: $\alpha(\theta; s, t) = e^{-t} \cdot [(e^t + 1)^\theta - 1]$ and $\beta(\theta; s, t) = 1 - e^{s-t}[(e^{-s+t} + 1)^\theta - 1]$. We can show that for any $s, t > 0$, $\alpha(\theta; s, t)$ and $\beta(\theta; s, t)$ satisfy $\alpha(0) = \beta(1) = 0$ and $\alpha(1) = \beta(0) = 1$, as well as other properties specified in Section 3. We use this family of functions to illustrate our structural properties, and have numerically validated the same properties hold under other families of functions. By fitting the data for the distal segments in Biasco et al. (2015), we obtained $t = 1.958$ and $s = 1.043$. See Online Appendix B for details and a graphic illustration of the $\alpha(\cdot)$ and $\beta(\cdot)$ functions.

The physician's decision rule is shown in Figure 4. The left panel of Figure 4 corresponds to the case in which the risk-to-reimbursement ratio of the advanced test is low, whereas the right panel corresponds to the case in which the risk-to-reimbursement ratio of the advanced test is high. In the left panel, when $\phi = 0$,

Figure 4. (Color online) Physician's Advanced Testing Policy as a Result of Conflict-of-Interest Level ϕ and Visual Assessment of the Angiogram θ



(a) Low risk-to-reimbursement ratio

(b) High risk-to-reimbursement ratio

Notes. In each panel, the shaded regions correspond to the cases in which the physician performs the advanced test, and the blank regions correspond to the cases in which the physician does not perform the advanced test. We use the following parameters for both panels: $r_d = \$267, r_p = \$623, r_a = \$91, b = \$2,542, h = \$1,312, l = \$162.3, t = 1.958$, and $s = 1.043$. We use two values of E—a low risk of \$200 in the left panel and a high risk of \$500 in the right panel.

the range of θ for which the physician performs the advanced test when θ centers around the threshold $\overline{\theta}^*(0) = 0.54$ (corresponding to a stenosis grade of 67%, using the transformation introduced in Online Appendix B), with a lower bound of 0.20 and an upper bound of 0.91 (corresponding to stenosis grades of 50% and 85.5%, respectively). These thresholds indicate the advanced test should be used for the majority of the cases with intermediate stenosis grades.

Our finding is consistent with clinical guidelines (see SCAI 2016 for the Society for Cardiovascular Angiography and Interventions' Quality Improvement Toolkit) that FFR is useful primarily for intermediate coronary lesions. It is also aligned with experts' recommendations: At a major teaching hospital in Maryland, the consensus among interventional cardiologists is that FFR should be performed for most of the intermediate stenosis grades in a major epicardial coronary vessel for a patient with an appropriate clinical indication.

One important difference between the recommendation from our model (i.e., performing FFR for most of the intermediate-lesion cases) and the decisions made on the ground is the uptake of FFR in the clinical practice is much lower than recommended—it is approximately 20%–25% (Wohns 2016) and significantly below the level suggested by our model. In addition, the uptake of FFR at many community nonteaching hospitals is much lower (or nonexistent), because the vast majority of FFR procedures are performed at major urban teaching centers (Pothineni et al. 2016).

The difference between the recommendation from our model and the decisions made on the ground is not just in the overall adoption rate of FFR, but indeed a *structural* one when we factor in financial incentives. To be specific, Proposition 3 shows that under a high conflict-of-interest level, physicians are incentivized to perform FFR for high-grade (as opposed to intermediate) coronary lesions, because the risk of reversing PCI decisions by performing FFR on a high-grade lesion is low. Thus, our findings have an important implication that the interventional cardiology literature has overlooked: it is not about the sheer quantity of FFR procedures; rather, it is about *which* patients should receive FFR procedures. Stated differently, the structure of physicians' testing decision making should be closely monitored and well tuned toward most ambiguous cases.

5.2. Reducing Procedural Risk of Advanced Test

Proposition 2 suggests that one way to incentivize the physician to perform the advanced test is to reduce its risk, which entails better design of the instruments involved in the advanced test (e.g., pressure wire in the case of FFR) and enhanced physician training (particularly in nonacademic medical practices with low uptake of the advanced test). As an example of related efforts, a Minnesota-based medical technology company has developed a "rapid exchange FFR system," which enables the use of workhorse coronary wires, potentially decreasing procedural complexity and patient risk (Diletti et al. 2015).

Although reducing the risk can lead to increased use of the advanced test, whether such a reduction would necessarily lead to improved patient welfare remains unclear.[6] Thus, we now use numerical experiments to generate implications for a patient's welfare, the formulation of which differs according to whether the advanced test is performed: (1) If the advanced test is not performed, expected patient welfare is $b\alpha(\theta) - h\beta(\theta)$ if a PCI procedure is conducted (i.e., if $\theta \geq \overline{\theta}^*$, according to Lemma 1), and $-l\alpha(\theta)$ if a PCI procedure is not conducted (i.e., if $\theta < \overline{\theta}^*$); (ii) if the advanced test is performed, expected patient welfare is $b \cdot \alpha(\theta) - \epsilon$.

We conducted extensive numerical experiments and obtained various results related to patient welfare. Among these results, one interesting and counter-intuitive finding is stated.

Observation 1. As ϵ decreases, counterintuitively, expected patient welfare may decrease.

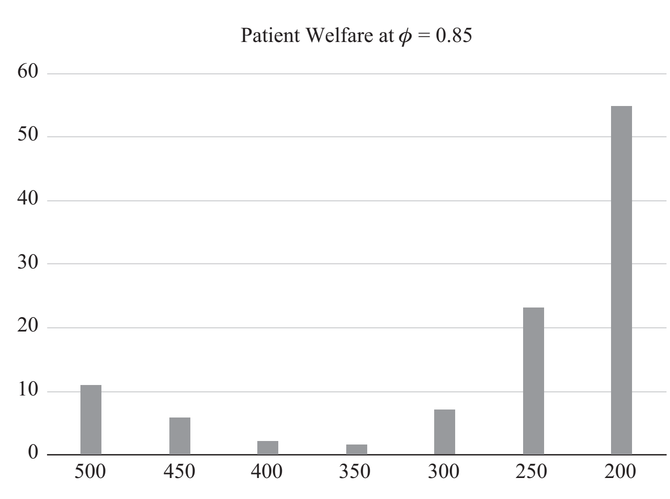
We use a numerical result to illustrate this point. We use the same parameters as those used in Figure 4 except that we vary the values of ϵ down from 500 to 200 in increments of 50.

Figure 5 demonstrates that in the case with a high conflict-of-interest level (in this case, $\phi = 0.85$), whereas patient welfare will improve when the additional risk associated with the advanced test (ϵ) experiences a significant decrease (e.g., from 500 to 200), the effect is nonmonotonic such that a moderate decrease in the additional risk may exacerbate patient welfare. This result is fairly surprising. We provide the intuition behind it, drawing from our key findings from Section 4. At $\epsilon = 500$, the practice environment has a high risk-to-reimbursement ratio because $\epsilon / r_a = 5.49 > h/(r_p - r_d) = 3.68$. In this case, by Proposition 2, the physician never performs the advanced test under an intermediate conflict-of-interest level (i.e., $\phi \in [0.7539, 0.8460]$). At $\phi = 0.85$, the physician's conflict-of-interest level is just outside of the intermediate range. By contrast, at $\epsilon = 450$, the risk-to-reimbursement ratio is still high but approaching low, and the range of the medium conflict-of-interest level is narrowing—the same ϕ now is further from the intermediate range [0.7649, 0.8318]—meaning the physician is more inclined to perform the advanced test, although the risk of the test is only modestly lower. In other words, a moderate risk reduction triggers a *disproportionally high* increase in the use of the advanced test. At $\epsilon = 300$, the risk-to-reimbursement ratio is now low because $\epsilon / r_a = 3.30 < h/(r_p - r_d) = 3.68$. The significant decrease in the risk leads to an improvement in social welfare compared with the case of $\epsilon = 450$. Nevertheless, compared with the case of $\epsilon = 500$, patient welfare at $\epsilon = 300$ is still lower because the decrease in the risk is accompanied by a disproportional increase in the use of the advanced test (with a risk level that remains high). The expected patient welfare constitutes an improvement from the case of $\epsilon = 500$ only when the risk is significantly decreased, such as when $\epsilon = 250$.

5.3. Providing Bonus for Conducting Advanced Test

In this section, from a hospital administrator's perspective, we propose providing a simple incentive scheme

Figure 5. Effect of ϵ on Average Patient Welfare Under $\phi = 0.85$



Notes. All parameters are the same as in Figure 4. (a) Low risk-to-reimbursement ratio. (b) High risk-to-reimbursement ratio.

for the advanced test and characterize its effect on patient welfare. Our proposed strategy holds all the other reimbursement rates at the current level, and is convenient to implement.

We denote by Δr_a the bonus provided to the physician for performing the advanced test. We conduct a simulation of the physician's decision making under different bonus levels for the advanced test. For each rate, we estimate the total expected per-case payment, which consists of payments for angiogram-based diagnosis, the potential advanced test, and the PCI procedure. We also examine the total expected number of PCI procedures and compare that number against the case with no conflicts of interest. This comparison provides an estimation of the extent of overstenting. Table 4 lists the expected per-case payment, percentage of inappropriate PCI cases (i.e., overstenting), and expected patient welfare under different values of Δr_a.

Table 4 shows a bonus of \$90, roughly equal to the current reimbursement level (\$91), leads to a reduction in overstenting, from 12.61% to 4.438%. A modest bonus, for example, \$30, can still be beneficial, with a 26.22% reduction in overstenting and a 5.073% increase in physician payment.

5.4. Bundled Payments

We have built a novel analytical framework of physician behavior in the interventional cardiology setting, highlighting the central importance of the endogeneity of advanced-testing decisions. In addition to the discussions in Sections 5.1–5.3, our framework has implications for emerging policy initiatives such as bundled payments. In terms of the design of bundles, our discussions with field experts revealed that using the same bundle regardless of whether a PCI procedure is conducted is infeasible because conducting a PCI procedure requires the physician to devote significantly more time and effort, compared with not conducting a PCI procedure. A feasible form of bundled payment would entail two bundles for cases with and without PCI procedures, respectively. Using our analytical framework, we can prove such a bundled-payment scheme will lead to a lower incentive for the physician to conduct the advanced test, leading to even more severe overstenting.

To see this connection, note from Figure 3 that a patient can go through one of the four pathways, which we refer to, from top to bottom, as pathways A, B, C, and D, respectively. Under the prevailing fee-for-service payment scheme, the physician's fees from pathways A, B, C, and D are r_p, $r_a + r_p$, $r_a + r_d$, and r_d, respectively. Suppose a bundled-payment scheme is implemented such that two bundles exist depending on whether the physician performs a PCI procedure. Let r_{AB} denote the bundled payment from pathway A or B, and let r_{CD} denote the bundled payment from pathway C or D. Under the bundled-payment scheme, the physician receives the same compensation for pathways A and B, and yet needs to exert more effort for pathway B because of an additional procedure (i.e., performing the advanced test). Thus, such a bundled-payment scheme actually provides a *disincentive* for the physician to perform the advanced test and potentially leads to more severe overstenting.

This bundled-payment scheme may provide an incentive for more thorough post-PCI care. However, the long-term impact of a PCI procedure is unlikely to be revealed in a time horizon specified in a typical bundled-payment scheme. Thus, this incentive may not be substantial.

Alternative payment models may be useful. For example, under a population-based payment model, the physician's reimbursement is based on the total number of patients served by the physician in a given period of time. Clearly, this payment model incentivizes the physician to minimize unnecessary procedures. Yet, such a payment model is hard to implement in the United States beyond a primary care setting (Burns and Pauly 2018).

Table 4. Effect of the Bonus Provided for Conducting the Advanced Test (Δr_a)

Δr_a(\$)	Expected per-case physician payment	Overstenting because of COI	Expected patient welfare	Percent increase in physician payment	Percent increase in expected patient welfare
0	502.7	12.61%	566.4	—	—
10	511.0	11.45%	570.3	1.651%	0.6886%
20	519.5	11.03%	574.3	3.342%	1.395%
30	528.2	9.303%	577.9	5.073%	2.030%
40	537.1	7.866%	581.4	6.843%	2.648%
50	546.1	7.866%	584.6	8.633%	3.213%
60	555.3	6.589%	587.7	10.46%	3.761%
70	564.6	5.805%	590.5	12.31%	4.255%
80	573.9	5.092%	593.2	14.16%	4.732%
90	583.4	4.438%	595.6	16.05%	5.155%

Notes. $\epsilon = 200$, θ is estimated using the distal segments data from Biasco et al. (2015) and follows a truncated normal distribution with a mean of 0.52 and a standard deviation of 0.251, and ϕ follows a truncated normal distribution with a mean of 0.5 and a standard deviation of 0.25. Other parameters mirror those in Figure 4(a). All the percentage-increase figures are relative to the baseline case (i.e., $\Delta r_a = 0$).

6. Unobserved Factors in Physician Decision Making

In certain cases, the interventional cardiologist may possess private information concerning a patient's potential benefit from a PCI procedure, based on the physician's professional expertise and experience with that particular patient. Thus, the same physician might make different diagnostic and treatment decisions for patients with comparable visually assessed angiographic stenoses.

Using a probabilistic approach pioneered by Rust (1987) and widely adopted in the literature (Su 2008, Huang et al. 2013), we now consider an alternative decision model to account for the setting in which the physician may have a private signal indicative of the patient's health status based on professional judgement and experience. The random error term is observable to the physician but not to external observers (e.g., researchers). Therefore, the physician's testing and treatment decisions may appear to an outsider to follow a random distribution.

Given θ, the visually assessed angiographic stenosis, the physician's utility from providing diagnostic service but not conducting PCI is (as in our main model) $\mu_{NP}(\theta) = \phi r_d + (1-\phi)[-l\alpha(\theta)]$. The physician's utility from conducting a PCI procedure can be represented as $\mu_P(\theta, \zeta) = \phi r_p + (1-\phi)[b\alpha(\theta) - h\beta(\theta) + \zeta]$, where ζ is the random error term capturing the physician's private signal indicative of the patient's utility gain from a PCI procedure. For tractability, following the convention in the literature (Su 2008, Huang et al. 2013), we assume ζ follows a logistic distribution with a cumulative distribution function of $H(\zeta) = 1/(1+e^{-\zeta/\psi})$ for some $\psi > 0$. Here the parameter ψ reflects the extent to which the physician's own expertise influences the clinical decision-making such that (1) as ψ approaches infinity, the clinical decision-making is entirely driven by the physician's own expertise, and (2) as ψ approaches zero, the clinical decision-making is entirely driven by the reading of the angiogram.

6.1. Angiogram-Guided Decision

When guided by angiogram only, the physician conducts a PCI procedure if and only if the utility from conducting a PCI procedure outweighs that of not conducting one; that is, $\mu_P(\theta,\zeta) \geq \mu_{NP}(\theta)$, which is equivalent to

$$\zeta \geq -\left[\frac{\phi}{1-\phi}\cdot(r_p - r_d) + (b+l)\cdot\alpha(\theta) - h\cdot\beta(\theta)\right].$$

Thus, we have the following result.

Lemma 4. *Given a visually assessed stenosis θ, the physician conducts a PCI procedure with probability $\frac{e^{\kappa(\theta,\phi)/\psi}}{1+e^{\kappa(\theta,\phi)/\psi}}$, where $\kappa(\theta,\phi) = (r_p - r_d)\cdot\phi/(1-\phi) + (b+l)\cdot\alpha(\theta) - h\cdot\beta(\theta)$.*

Note $\kappa(\theta,\phi)$ increases in both ϕ and θ, which gives the following corollary.

Corollary 4. *The physician's probability of conducting a PCI procedure increases in both ϕ and θ.*

Corollary 4 echoes the result from our main model (i.e., Lemma 1) in stating the physician is increasingly likely to conduct a PCI procedure given a more severe visually assessed angiographic stenosis or under a higher conflict-of-interest level.

6.2. Advanced Test Decision

If the physician does not perform the advanced test, the physician's utility is $\max\{\mu_P(\theta,\zeta), \mu_{NP}(\theta)\}$. If the physician performs the advanced test, the physician's expected utility representation is the same as in our main model; that is,

$$\mu_a(\theta) = \phi\cdot\{(r_p - r_d)[1-\beta(\theta)] + r_d + r_a\} + (1-\phi)[b\cdot\alpha(\theta) - \epsilon].$$

The physician performs the advanced test if and only if

$$\mu_a(\theta) \geq \max\{\mu_P(\theta,\zeta), \mu_{NP}(\theta)\}.$$

We present the physicians' advanced testing in the proposition that follows. For ease of notation, we define the following two thresholds:

$$\epsilon^{(0)}(\theta,\phi) = \frac{\phi}{1-\phi}\cdot\{r_a + (r_p - r_d)[1-\beta(\theta)]\} + (b+l)\alpha(\theta), \text{ and}$$

$$\hat{\kappa}(\theta,\phi) = \frac{\phi}{1-\phi}\cdot[(r_p - r_d)\beta(\theta) - r_a] + \epsilon - h\beta(\theta).$$

Proposition 5. *Given the visually assessed angiographic stenosis θ, conflict-of-interest level ϕ, and additional risk of the advanced test ϵ,*

i. *If $\epsilon > \epsilon^{(0)}(\theta,\phi)$, the physician never performs the advanced test.*

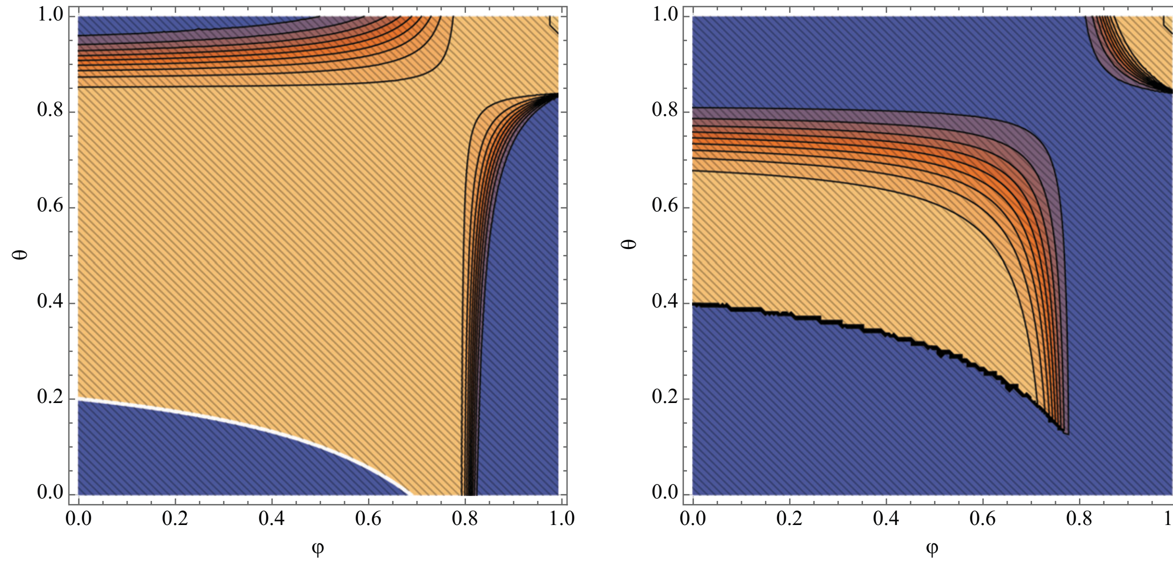
ii. *If $\epsilon \leq \epsilon^{(0)}(\theta,\phi)$, the physician performs the advanced test with a probability of $\frac{1}{1+e^{\hat{\kappa}(\theta,\phi)/\psi}}$, and does not perform the advanced test with a probability of $\frac{e^{\hat{\kappa}(\theta,\phi)/\psi}}{1+e^{\hat{\kappa}(\theta,\phi)/\psi}}$.*

Next, based on part (ii) of Proposition 5, we examine the monotonicity of the physician's probability of performing the advanced test with respect to θ. We have the following corollary.

Corollary 5. *When $\epsilon \leq \epsilon^{(0)}(\theta,\phi)$, the physician's probability of performing the advanced test is increasing in θ if and only if $\phi < \phi^{(0)}$.*

We now visualize the physician's probability of performing the advanced testing, with respect to the conflict-of-interest level ϕ and the visual assessment of

Figure 6. (Color online) Contour of the Physician's Probability of Performing Advanced Testing, with Respect to Conflict-of-Interest Level ϕ and Visual Assessment of the Angiogram θ



(a) Low risk-to-reimbursement ratio (b) High risk-to-reimbursement ratio

Notes. In each panel, a darker color indicates a lower probability, and a lighter color indicates a higher probability. We use $\psi = 50$. Other parameters used in the two contour plots correspond to those used in the two plots in Figure 4.

the angiogram θ and show the contour plots in Figure 6. We now provide some intuition for a part of the decision patterns shown in Figure 6. Consider the extreme case of $\theta = 0$ and $\phi = 1$, which represents a fully revenue-driven physician serving the least severe patient. Because $\epsilon^{(0)}(\theta, \phi) = +\infty > \epsilon$ and $\hat{\kappa}(\theta, \phi) = \frac{\phi}{1-\phi} \cdot [(r_p - r_d)\beta(\theta) - r_a] + \epsilon - h\beta(\theta) = +\infty$ (noting from our assumption that $r_p - r_d - r_a > 0$). Thus, by Proposition 5, the physician would not perform the advanced test. Now, as θ increases, the physician does not perform the advanced test until $(r_p - r_d)\beta(\theta) - r_a < 0$, at which point we have $\hat{\kappa}(\theta, \phi) = -\infty$ and the physician would perform the advanced test with a probability of 1.

Similarly, for any given $\phi \in (\phi_0, 1)$, starting from $\theta = 0$, where $\epsilon^{(0)}(\theta, \phi) = \frac{\phi r_a}{1-\phi}$ and $\hat{\kappa}(\theta, \phi) = \frac{\phi}{1-\phi} \cdot [r_p - r_d - r_a] + \epsilon - h$. If $\epsilon > \epsilon^{(0)}(\theta, \phi)$, the physician never performs the advanced test. As θ increases, $\epsilon^{(0)}(\theta,\phi)$ increases, it is more likely that $\epsilon \leq \epsilon^{(0)}(\theta,\phi)$. On the other hand, if $\epsilon \leq \epsilon^{(0)}(\theta, \phi)$, by Proposition 5, the probability of testing $(\frac{1}{1+e^{\hat{\kappa}(\theta,\phi)/\psi}})$ is increasing in θ when $\phi > \phi_0$.

Incorporating unobserved factors in physician decision making enables us to refine our understanding of the physician's advanced testing decision. Our results show the physician's advanced testing decision exhibits patterns similar to those in Figure 4. Thus, the key insights from our main model hold, validating the robustness of our findings and their policy implications.

7. Conclusions

Coronary heart disease leads to one out of every six deaths in the United States, more than any other cause of death (Go et al. 2014). However, decision making in a cardiac catheterization laboratory—an indispensable segment of cardiology patient care—has not been well understood. Whereas the broad consensus among the interventional cardiology community is that PCI procedures are being significantly overused (Huang and Rosenthal 2015), the solution to the problem of inappropriate PCI procedures is far less apparent, due to ambiguity and nuance in clinical practices.

Our study represents an initial attempt to analytically model interventional cardiology decision making by jointly considering clinical ambiguity and conflicts of interest. We analyze a physician's PCI decision guided solely by eyeballing the coronary angiogram and show the subjectivity of visually assessing angiographic stenosis may interact with revenue incentives. Then, we incorporate the option to perform the advanced test and characterize the physician's advanced testing decision under various conflict-of-interest levels.

These results lead to practical implications for strategies for mitigating overstenting, including (1) reducing the risk of the advanced test, (2) providing a bonus for performing the advanced test, and (3) implementing a bundled-payment scheme.

Our analytical framework provides managerial implications that may be tested in the field using experimental approaches or with empirical estimation. We show an important driver of the physician's decision-making process is the conflict-of-interest level, which may vary across hospital types (teaching versus nonteaching, urban versus rural, and private versus safety net). Thus, our research calls for further inquiry into the extent of competing interests in healthcare delivery, which has yet to be rigorously estimated using empirical approaches.

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Endnotes

[1] Throughout the paper, we focus on the case of nonacute PCI cases, because acute PCI cases are rarely inappropriate; see Section 2 for details.

[2] The following reported scenario reflects this issue: "Some physicians had indicated in medical records that the patients had blockages of 80 to 90% when a later, more scientific analysis of a sampling of cases revealed the blockages had ranged from 33 to 53%" (Abelson and Creswell 2012).

[3] Here, we use conflicts of interest to refer to situations in which a healthcare provider's interests deviate from patients', and we allow a continuum of conflicts of interest. The term has been used in various other settings (Weinfurt et al. 2008) in which a physician's medical decision is influenced by financial interests, leading to guidelines for managing this conflict at leading institutions (Camilleri and Cortese 2007, Steinbrook 2009) and studies about the optimal reimbursement levels for coronary revascularization (Tarricone et al. 2004).

[4] According to Mark Hlatky, Professor of Cardiovascular Medicine at Stanford University, "When a doctor does the test and finds a significant blockage, most stents are placed immediately, during the same procedure. If a patient has reservations about having a stent put in, at that point, it's too late to discuss them" (Brewington 2010). We expect modeling the role of patients to be an important topic of future research as shared decision making gains traction in the medical community.

[5] The minimal level of narrowing of consideration for PCI decisions is substantially higher than zero blockage. For example, $\theta = 0$ may represent one conventionally used criterion according to which PCI procedures would not be considered for lesion < 50%. The expression $\theta = 1$ corresponds to a level of blockage close to 100% but strictly below 100%; a 100% blockage in a stable CAD case, referred to as chronic total occlusion, would not fit into the model described here. Later, in our numerical experiments, consistent with Biasco et al. (2015), $\theta = 0$ corresponds to an angiographic stenosis grade of 40%, and $\theta = 1$ corresponds to an angiographic stenosis grade of 90%.

[6] In the setting of interventional cardiology, as in many other healthcare settings, most of the resources are already available with marginal operating costs that are negligible compared with high staffing and investment costs, and the primary consequence of overstenting is patient welfare. The payments are cancelled out in the social-welfare calculation once the payer is incorporated. Thus, we can use patient welfare as a proxy for social welfare.

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