Tort Reform and Innovation[1]

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Abstract

Current academic and policy debates focus on the impact of tort reforms on physicians' behavior and medical costs. This paper examines whether these reforms also affect incentives to develop new technologies. We develop a theoretical model which predicts that the impact of reducing liability risks for physicians on innovation may be positive or negative, depending on the characteristics of the technology. Empirically, we find that, on average, laws that limit the liability exposure of healthcare providers are associated with a significant reduction in medical device patenting. Tort reforms have the strongest impact in medical fields in which the probability of facing a malpractice claim is the largest, and they do not seem to affect the amount of new technologies of the highest and lowest quality. Our results underscore the importance of considering dynamic effects in the economic analysis of tort laws.

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1 Introduction

Economists have long recognized the crucial role of innovation for economic growth. How to design effective innovation policies is a central question in the innovation and public policy literatures. Innovation policies may impact both the *level* of R&D investments and innovative output, as well as their *direction*; i.e., the types of technologies developed (Acemoglu, 1998). To encourage R&D, governments typically implement a variety of policies directly targeting innovation such as patents and subsidies. Only recently, economists have recognized that policies not directly targeted at innovation may also have large impacts on R&D incentives and the direction of technological progress (Finkelstein, 2004). Documenting and quantifying these indirect and dynamic effects is crucial not only to understanding the determinants of innovation activities, but also to evaluating the costs and benefits of policy reforms in general.

The objective of this paper is to examine the innovation investment response to a prominently debated public policy: tort reform. Torts are actions that injure someone and are recognized by law as grounds for a lawsuit. The role of the tort system is to deter people from injuring others and compensate those that are injured. An important class of torts related to professional negligence is medical malpractice. A danger prominently voiced in public debates is that large settlements arising from medical malpractice litigation lead doctors to practice "defensive medicine"–i.e., to perform excessive tests and procedures because of concerns about malpractice liability. Policy debates typically contrast the high costs of defensive medicine procedures with their low expected benefits to patients. A number of studies have investigated the relationship between the tort system and treatment intensity or medical expenditures, and they provide evidence that changes in liability concerns influence physicians' behaviors (inter alia see Kessler and McClellan, 1996; Currie and MacLeod, 2008).

In addition to their effects on procedure use and malpractice claims, tort reforms may also affect R&D investments and technological change. In particular, a number of law scholars have warned about a possible "chilling effect" of the current tort system on innovation; that is, high damage awards and the court's reliance on custom may reduce physicians' willingness to adopt new, but riskier technologies, even if they are potentially superior to customary treatments (e.g., Parchomovsky and Stein, 2008; Greenberg, 2009; and Priest, 2011). This idea that 'liability retards innovation' has become a key argument for tort reform advocates, and has gained substantial ground over the years in courts and Congress. A typical counter-argument is that high liabilities may also encourage innovation because they induce physicians to adopt

innovative technologies that are themselves safer or help physicians manage risks. Despite these claims, the empirical literature on the relationship between liability risk and innovation is scarce. We aim to address this gap by studying the impact of tort reforms on innovation in the medical device sector, a field of technology closely linked to malpractice litigation.

To illustrate the channels through which tort reforms may affect innovation incentives, we begin our analysis with a simple theoretical model. In our framework, physicians adopt medical technologies considering both their expected effectiveness in addressing patients' medical conditions and the likelihood of potential malpractice liability. Tort reforms, such as the introduction of caps on damage awards, will reduce physicians' expected liability cost and influence their adoption decisions. Consistent with the idea that high liabilities chill innovation, our model predicts that a reduction in the expected liability risk will *increase* physicians' propensity to use riskier technologies with high effectiveness. However, our analysis also shows an additional effect of tort reforms—i.e., they *reduce* the propensity of physicians to "defensively adopt" low-risk technologies that help them to avoid suits. These shifts in adoption affect upstream R&D investments, and the overall impact on the development of new technologies depends on the relative strengths of the two effects.

While our theoretical framework shows that the overall effect of tort reforms on innovation is ambiguous, it provides a testable prediction. Tort reforms are more likely to reduce innovation incentives in technology fields characterized by higher risks of malpractice claims. Intuitively, in these fields, it is likely that physicians adopt new technologies mainly for defensive reasons. Thus, if the expected liability cost is reduced, the incentives to use these technologies decrease, resulting in an overall decline in innovation incentives.

Empirically, we combine standard measures of innovation, based on US patent data, with data on state tort reforms collected by Currie and MacLeod (2008) for the period 1985-2005. We use the inventor address information provided by the United States Patent and Trademark Office (USPTO) and the application year of a patent to link patents to U.S. state-years. We also exploit the USPTO 3-digit technology classification to identify medical instrument patents. The class of tort reform central to our empirical analysis is the introduction of caps on non-economic damages; that is, damages other than monetary losses, such as pain and suffering. These damages typically comprise a substantial fraction of total awards and represent the main focus of tort reform advocates.

Our main result shows that patenting in medical instruments is reduced by roughly 14

percent in the presence of caps on non-economic damages. This negative effect suggests that, on average, the demand for new technologies that high liabilities generate through defensive-adoption exceeds their negative chilling effect on medical device innovation. This finding is robust to a wide variety of alternative specifications and controls. In particular, results are similar if we exclude from the sample a small number of states for which caps on non-economic damages affect only medical malpractice rather than general torts. Moreover, we show that our findings are not driven by the largest states or by the largest medical device producers. We also run a placebo test that indicates no effect of tort reforms in the sample of non-medical, measuring and testing instruments.

Extending our baseline model, we show that tort reforms generate a gradual decline in patenting that stabilizes about four years after the reform. We also show that these reforms tend to have a localized effect; i.e., changes in patenting are predominantly driven by innovators located in the reforming state. We argue that the local nature of the estimated effect may be explained by a number of features of medical device innovation. Notably, the literature has documented extensive involvement of physicians in the innovation process, either directly as inventors or indirectly through providing ideas and feedback for device designs (Shaw, 1985 and von Hippel, 2006). Indeed, a sizable fraction of the negative impact of tort reforms appears to be driven by the patenting activity of physician inventors located in the state.

To further test the predictions of the model, we examine two dimensions of heterogeneity in the effect of tort reforms. First, we show that the impact of tort reforms is much more pronounced for specialities with a high frequency of malpractice claims (such as surgery and orthopedics). Conversely, the effect is small and statistically insignificant for medical fields with few malpractice claims (such as dental and optics). Second, exploiting patent citations as a proxy for technological value, we document a non-monotonic U-shaped relationship between the effect of tort reforms and innovation quality. Caps on damages have no statistically significant effect on innovation at the lowest and the highest quality quintiles. The effect is negative, statistically significant and of large magnitudes at intermediate quality levels.

Taken together, our findings indicate that tort reforms affect both the level and the direction of innovation, and that an effective assessment of these policies should consider both their static impact on patients, medical costs, and their dynamic effects on medical technologies. While, on average, caps on damages appear to reduce the propensity to innovate, our analysis shows that this effect is highly heterogeneous and depends on the characteristics of both the

technologies and the medical fields.

The paper is organized as follows. Section 2 summarizes the related literature. In Section 3, we present a simple model that links tort reforms with innovation incentives. Section 4 describes the data and the econometric specification. Section 5 presents the estimates of the average effect of tort reforms on medical device patenting, and Section 6 shows that the impact of tort reform is heterogeneous and depends on the characteristics of the field and the innovation. We conclude with a brief discussion of the findings.

2 Related literature

Our paper is related to studies that investigate the determinants and direction of innovation, in line with the induced-innovation and directed technical change literatures. In the context of pharmaceuticals, a number of papers have investigated the impact of variations in potential market size, exploiting shifts in population demographics (Acemoglu and Linn, 2004), the introduction of Medicare Part D (Blume-Kohout and Sood, 2013), and variations in effective patent life (Budish et al., 2015). More specifically, our paper is related to studies that examine how public policies focusing on achieving some social goal other than innovation affect innovation. In the health sector, Finkelstein (2004) exploits three different policy changes designed to increase the usage of preexisting vaccines and finds that these policies are associated with a 2.5-fold increase in clinical trials for new vaccines. Acemoglu et al. (2006) find that the introduction of Medicare was not associated with an increase in drug consumption among the elderly; and consistent with this, they find no evidence of an increase in the approval of new drugs targeting diseases that affect the elderly. In the energy and environment sector, Jaffe and Palmer (1997) conclude that environmental compliance standards increase R&D spending at the firm level.

Our analysis draws on the literature studying the relationship between legal liabilities and medical practice.[1] Most studies in this literature exploit the variations provided by state tort reforms. Kessler and McClellan (1996) examine Medicare beneficiaries treated for serious heart diseases and find that tort reforms lead to reductions in medical expenditures of five to nine percent without substantial effects on mortality or medical complications. Similarly,

[1] Another stream of studies examines the effects of tort reforms on malpractice claims such as the frequency and severity (e.g., Danzon, 1984; and Avraham, 2007), and malpractice insurance-related outcomes, such as insurers' reported losses, mean payments, and insurance premiums (e.g., Barker,1992; and Viscusi and Born, 1995). For an overview of the malpractice system and the effects of tort reforms, see the survey by Kessler (2011).

Avraham and Schanzenbach (2015) find that the probability of heart patients receiving a major intervention drops by five percent after a state implements non-economic damage caps. These results provide evidence for the practice of defensive medicine when liability risks are high. Other papers provide more-nuanced evidence on the influence of liability risks on physician behaviors. Currie and MacLeod (2008) find that caps on non-economic damages increase, while the joint and several liability rule decreases the use of cesarean sections. Shurtz (2014) shows that the effects of tort reforms may depend on physicians' financial incentives. Frakes (2013) shows that states' utilization rates of various treatments and diagnostic procedures changed substantially following the adoption of a rule requiring physicians to follow national, as opposed to local, malpractice standards of care. Frakes and Jena (2016) show that changes in clinical standards can induce higher levels of health care quality.

The only empirical study that we are aware of linking liability and innovation is by Viscusi and Moore (1993), who show that, on average, higher liability costs increase firms' R&D intensity. Their paper differs from ours in a number of dimensions. Theoretically, they study the direct effect of product liability on firms' R&D investment, whereas, in our model, changes in liability risks affect innovation indirectly, as they first influence physicians' demand for new technologies. Empirically, they study the impacts of product-liability insurance cost using a cross-industry dataset covering large firms between 1984 and 1987. We examine the effects of state tort reforms on all medical device patenting in the period of 1985 and 2005.

Our paper also relates to the literature on innovation and technology diffusion in the medical device industry. Clemens (2013) finds that the introduction of Medicare and Medicaid had a positive effect on U.S.-based medical equipment patenting. Von Hippel (2006) and Chatterji and Fabrizio (2014) study the role of users in medical device innovation. Grennan and Town (2015) examine the impact of regulatory testing requirements for medical devices on innovation diffusion. Stern (2015) shows that medical device innovation incentives are shaped by the regulatory approval process. Nistor and Tucker (2015) show that the Food and Drug Administration's (FDA) decision to allow for third-party certification of medical devices led to more adverse medical events.

3 Theoretical model

In this section, we develop a simple theoretical model to explore the effects of tort reforms on innovation incentives. The setting departs from the literature that studies the effect of tort

reform on the choice of medical procedures (Currie and MacLeod, 2008; Schurtz, 2014) by introducing an innovation process that endogenizes the set of procedures available to physicians. In our framework, innovations are characterized by multidimensional heterogeneity, as in Weyl and Tirole (2012). Policy reforms affect technological progress through their impact on downstream technology adoption, which, in turn, shapes upstream R&D investments, as in Aghion et al. (2015).

3.1 Basic framework

We consider a medical field with a representative (consumer) physician and an innovator. We assume that the physician's utility from adopting medical technology i consists of the expected effectiveness of addressing the patient's medical conditions and the expected cost of medical malpractice liability, similar to Currie and MacLeod (2008) and Schurtz (2014). A medical technology, i, is thus characterized by two parameters: $b_i \in [0,1]$ and $r_i \in [0,1]$, where b_i is the expected effectiveness of the treatment, and r_i is the probability of a bad patient outcome, which may arise because of the inherent uncertainty of treatment outcomes and uncertainty in execution.

The expected liability given a bad outcome is H, which captures the (conditional) probability that a bad patient outcome would result in a malpractice claim and the expected cost that the physician expects to face if involved in such a dispute. The literature on medical malpractice points out that even when physicians are insured against claims for monetary damages, they still suffer from malpractice disputes due to additional costs such as time loss, stress, and damage to the physician's reputation.[2] We model a tort reform as a *decrease* in H, which may operate through two channels: (i) a reduction in the frequency of malpractice claims given bad patient outcomes;[3] and (ii) a reduction in the expected costs associated with malpractice disputes.

The physician's utility, when she adopts technology i is

$$U_i = b_i - r_i H. \tag{1}$$

[2] As discussed in Currie and MacLeod (2008), payments made on behalf of a physician to settle malpractice claims are registered in the National Practitioners' Data Bank (NPDB), which hospitals, health care professionals and lawyers often access. Seabury et al. (2013) analyze data from 40,916 physicians covered by a nationwide insurer and find that the average physician spends 50.7 months (about 11 percent of a forty-year career) with an unresolved, open malpractice claim.

[3] For example, Avraham (2007) finds that caps on non-economic damages enacted in a state significantly decrease the number of cases per 1,000 doctors by 10-15 percent.

For a simple micro-foundation of our setting, consider an environment in which technology i is characterized by a distribution of potential patient outcomes $y \sim G_i$, with mean μ_i and support $[0, 1]$. A dispute arises only if the realized outcome is below a certain threshold $\underline{y}$. The utility of the physician is then $U_i = \mu_i - G_i(\underline{y})H$, which is equivalent to equation (1) once we set $b_i = \mu_i$ and $r_i = G_i(\underline{y})$.

The innovator has an idea for a new patentable technology, which we denote as N. The medical field is characterized by a dominant standard technology O, which is freely available to physicians. We model the idea-generation process following Scotchmer (1999) and assume that b_N and r_N are independent draws from the uniform distribution over the interval $[0, 1]$. We assume that b_O and r_O are exogenously given and that $U_O > 0$ and $U_O < 1 - H$. These assumptions rule out extreme outcomes and ensure that there are no regions in which the old technology is dominated or dominant for all values of r_N.

An idea can be developed into a new technology through an R&D process. Successful development takes place with probability $p(x) = x$ if the innovator incurs a research cost $C(x) = x^2/2$. As in Aghion et al. (2015), we refer to x as the "innovation intensity," which captures the likelihood of successfully developing a new technology.

The timing of the game is as follows. The innovator draws the idea, observes b_N and r_N and decides whether and how much to invest in R&D to develop the new technology. If the new technology is developed, the innovator makes a take-it-or-leave-it offer to the physician, who then decides whether to adopt N or O. If N is not developed, the physician adopts O.

For an illustrative example of how liability risks influence the physician's choice between alternative technologies, consider the case of heart-attack patients. Avraham and Schanzenbach (2015) show that the probability of receiving a major intervention in the form of either an angioplasty or a bypass, instead of drug management and monitoring, declines by 1.25 to two percentage points after non-economic damage caps are enacted. This provides evidence that damage limitations can reduce treatment intensity. Furthermore, they also find evidence of substitution between major interventions. Angioplasty declines by roughly two percentage points after caps are imposed, while bypass surgery, which is more invasive and remunerative than angioplasty, rises by 0.5-0.6 percentage points.

More broadly, we can also interpret the two technologies as complements. When bundled together, the new technologies help the physician improve the patient outcome and/or better manage the risk. In other words, U_N is the utility of the bundle combining the old and the new

technologies, and the innovator is rewarded with the extra utility generated to the physician when the new technology is included in the bundle. Examples include a surgical device allowing for an easy delivery of the fetus during a cesarean section when fetal head is deeply wedged in the pelvic cavity; an apparatus and method that position a patient for rapid and effective endotracheal intubation; and a device delivering bioactive materials that help wound recovery after surgeries.

Finally, in our model, physicians act as users of medical devices, not as inventors. User's involvement in the process of medical device innovation is well documented in the economics and management literature (Shaw, 1985; von Hippel, 2006, Chatterji et al., 2008). Even though the typical form of user involvement is through providing ideas and feedback for device designs and innovative features, many physicians are also inventors. Chatterji et al. (2008) document that about 20 percent of medical device patents have at least one physician listed as an inventor. While our assumption that the physician and the innovator are separate players captures the typical case, our theoretical results generalize to the case in which physicians are also innovators, as long as they can appropriate in part or fully the rents from commercialization.[4]

3.2 Tort reforms and innovation incentives

If technology N is developed, the innovator makes a take-it-or-leave-it offer to the physician for a transfer, t. The physician decides whether to accept the offer, which yields a payoff of $U_N - t$, or to adopt the old technology, which yields U_O. This implies that the payoff of the innovator will be either $U_N - U_O$ or zero, depending on whether the new technology offers the physician lower utility than the old technology.[5]

The physician will adopt the new technology if $U_N \geq U_O$, which occurs when b_N is above the following threshold:

$$b_N^* = b_O - H(r_O - r_N). \tag{2}$$

Figure 1 illustrates the parameter region in which the new technology is adopted and the shift associated with tort reforms (i.e., a decrease in H). For a fixed level of liability, H, physicians

[4] Theoretically, a comparison of innovation incentives with and without the physician also being the inventor would require additional assumptions on the opportunity cost of time for the two types of inventors, as well as on the magnitude of the frictions that might inhibit informational feedback to a separate player. It is, thus, an empirical question of which type of inventors might be more responsive to tort reforms. We explore this issue in Section 5.2.

[5] Our results are robust to replacing the take-it-or-leave it offer with a Nash bargaining protocol in which the surplus is split between the innovator and the physician.

trade off technology quality with the risk of malpractice litigation. Riskier technologies ($r_N > r_O$) are adopted as long as their quality ($b_N - b_O$) is high enough. Conversely, safer technologies are adopted only if their quality is not too low.

A decrease in H rotates the adoption threshold clockwise. The result highlights that a tort reform has different effects on adoption, depending on the characteristics of the new technology. First, there is an increase in the adoption of high-quality but riskier technologies. This is consistent with tort reforms mitigating the concern that high liability exposure makes physicians reluctant to adopt new technologies (i.e., the 'chilling effect' of the current tort system on innovation suggested by Parchomovsky and Stein, 2008). Second, in contrast, there is a reduction in the adoption of low quality and safer technologies. This is consistent with the argument that high liability exposure motivates physicians to use low-risk technologies even if their effectiveness is limited, and that tort reforms help mitigate this 'defensive-adoption' incentive. Finally, there is no effect on the adoption of high-quality/low-risk or low-quality/high-risk technologies.

FIGURE 1 HERE

The overall effect of a tort reform on technology adoption is, therefore, ambiguous. The following proposition shows that when the old technology is sufficiently risky, in the absence of tort reforms, the incentive to avoid malpractice claims by defensively adopting safer technologies dominates the chilling effect of high liabilities. As a result, a tort reform would result in an overall decrease in the propensity to adopt new technologies. That is,

Proposition 1 *A decrease in H generates an overall decrease in the propensity to adopt new technologies if and only if the old technology is sufficiently risky (i.e., $r_O > 1/2$).*

Proof. See online appendix 1. ■

So far, our analysis has focused on the effect of tort reform on technology adoption. The overall impact of a tort reform on innovation combines its impact on adoption with the effects on the incentives to invest in R&D. For technologies that are going to be adopted ($U_N \geq U_O$), the profits from a successful innovation are $U_N - U_O$, and the innovator will invest in R&D, x, to the point at which the marginal cost of R&D equals its marginal benefits.

Generally speaking, tort reforms may have a positive or a negative effect on innovation incentives, depending on the type of the new technology. At the extensive margin, because tort reforms affect the physician's adoption decisions, some technologies become profitable after the

reform while others are no longer profitable. The former experience an increase in the innovation intensity while the latter experience a drop. At the intensive margin, for technologies that are adopted regardless of the liability regime, tort reforms affect their profit incentives. Recall that the profit from a successful innovation is equal to $b_N - b_O - H(r_O - r_N)$. Therefore, a reduction in H increases innovation intensity for technologies with $r_N > r_O$ and decreases innovation intensity for those with $r_N < r_O$. Finally, the relative magnitudes of the opposing effects (extensive and intensive margins combined) on innovation incentives would depend on how the quality of the new technology compares to the old technology, as the relative importance of safety consideration is different. The characterization of the optimal R&D intensity shows that the overall effect of a tort reform on innovation incentives depends on the risk level of the existing technology.

Proposition 2 *The impact of a decrease in H on innovation intensity is negative when the old technology is sufficiently risky ($r_O > 1/2$) and ambiguous otherwise ($r_O \leq 1/2$).*

Proof. See online appendix 1. ■

In the proof of Proposition 2, we show that when $r_O > 1/2$, the negative impact of tort reform on innovation dominates regardless of the quality and, hence, the overall net effect is negative. Intuitively, when the risk level of the old technology is high enough, a large number of new technologies are developed and generate high profits mainly for defensive reasons. Thus, if a reduction in H is implemented, the profitability of these technologies declines and this reduces innovation incentives. When the risk level of the existing technology is relatively low ($r_O < 1/2$), we show that the positive impact of tort reform on innovation intensity dominates for technologies of high quality, rendering the overall net effect of tort reform ambiguous.

To summarize, our simple model shows that tort reforms have an ambiguous effect on innovation. Moreover, it generates a testable prediction: the effect of tort reform on innovation is more likely to be negative in technology fields characterized by a higher risk of malpractice litigation.

3.3 Discussion of the main modeling assumptions

The model builds on a number of assumptions that warrant additional discussion. First, in describing the idea-generation process, we assume that parameters are drawn from uniform distributions. Uniform distribution is a common assumption when modeling ideas, given the abstract nature of the creative process (Scotchmer, 1999). An important feature of our model

is that even though ideas are uniformly drawn, the distribution of ideas developed into technologies is not restricted to being uniform. The innovator chooses endogenously how much to invest in development, and she invests more when ideas are more profitable.[6]

Second, our framework assumes that b and r are independently distributed. A priori, there is no reason to impose correlation between b and r in the idea space. Under the interpretation of b and r as features of a distribution of patient outcomes, the correlation between b and r requires restricting the shapes of the outcome distributions across ideas. For developed ideas, the correlation between b and r arises endogenously in our model and depends on H.[7]

Third, for simplicity, our model does not include physicians' financial incentives. Therefore, the parameter b should be interpreted as a combination of the utility that the physician attaches to patients' wellbeing and her own financial incentives. These financial incentives typically depend on patients' insurance plans, as is captured in Schurtz (2014). In our empirical analysis, we will show that our estimates do not change when we control for the extent of public and private insurance coverage in a state.

Fourth, we can extend our model to include negligence standards and customary practices. Recall that the expected liability cost H can be interpreted as the product between the probability of a malpractice claim given a bad patient outcome and the expected costs associated with the claim. One way to include standard practice is to assume that both elements in H are smaller for the old technology. This can take place because plaintiffs (and their lawyers) may be less likely to bring a claim against a technology consistent with customary practice. In addition, courts may dismiss the case sooner and the likelihood of finding the defendant liable may also be smaller. We can show that the qualitative predictions of our model are robust to this extension, but that tort reforms generate a decline in technology adoption and innovation incentives under more stringent conditions in the presence of negligence standards.[8] As dis-

[6] More restrictive models would impose assumptions which link the liability regime and the characteristics of the old technology on the distribution of ideas. A natural assumption along these lines would be that when H and r_O are large, demand from defensive medicine leads to a greater likelihood of drawing ideas which reduce risk. The testable predictions in this case are similar to the one of our baseline model, with an even stronger negative effect of a reduction in H on innovation when the old technology is risky.

[7] If we extend the model by imposing a negative correlation between b and r, we would expect a lower impact of a tort reform on innovation incentives. This is because negative correlation renders more likely ideas with high effectiveness and low risk (which are developed independently of the malpractice regime) and ideas with high risk and low effectiveness (which are not developed even in the presence of caps on damages). Conversely, we would expect positive correlation between b and r to amplify the impact of tort reforms.

[8] The advantage that the standard technology enjoys can be captured with a parameter, $\beta_O < 1$, which reduces the expected liability cost for the old technology from H to $\beta_O H$. Propositions 1 and 2 continue to hold

cussed in Frakes (2015), it is important to notice that there are various ways in which choices of treatments and devices affect courts' perceptions and determination of liability. Apart from the case discussed above, we may also have the opposite case in which the new technology reduces the likelihood that a court determines that the physician is negligent.[9]

4 Data and methods

We begin with a U.S. state-year panel dataset measuring tort reforms during the period 1985-2005. The main source of data on tort reforms is the dataset compiled by Currie and MacLeod (2008).[10] We merge this panel with the United States Patent and Trademark Office (USPTO) patent dataset to measure patenting activity across U.S. states during our sample period. We use the address information of the first inventor and the application year of a patent to aggregate patents to the state-year level. Each patent is classified by the USPTO using 3-digit technology classes, and we exploit this detailed classification system to identify medical instrument patents.[11] We also obtain control data, including the gross product, the population, and the number of physicians in a state.[12]

USPTO patents offer a unique source of data for large-scale studies on innovation. Nonetheless, certain qualifications should be kept in mind. First, not all inventions are patented, but the innovation literature has shown that technologies with greater impact on social welfare and economic growth are more likely to be patented (Pakes and Griliches, 1980). Second, innovation is a process for which it is impossible to measure the origin. Relative to alternative measures, such as an FDA-approved device and the location information of its manufacturer, the application date of a patent and the location of the inventors are probably the best available

except that the cut-off for r_O is now higher ($1/(2\beta_O)$ instead of $1/2$).

[9] For example, in a landmark medical malpractice case, the District of Columbia Court of Appeals held a hospital liable for not using a pulse oximeter in 1990, despite expert testimony claiming that the use of pulse oximeters was not yet a standard practice (Washington v. Washington Hosp. Ctr., 579 A.2d 177).

[10] They construct the data employing several law students to independently look up and record all state statutes that implemented tort reforms and any decisions that subsequently affected the status of these statutes. Their data correct a number of entries in the information provided by the American Tort Reform Association which sometime misses earlier tort reforms and cases in which the laws were overturned. They also take into account that sometimes state legislatures codified practices that were already established under common law so that what appears to be a law change is not.

[11] Specifically, we follow a list provided by the USPTO indicating patent classes related to medical devices: http://www.uspto.gov/web/offices/ac/ido/oeip/taf/meddev.htm.

[12] These data are obtained from the US Census and the BEA. Information on the number of physicians is not reported in the US Census Statistical Series for the years 89, 91 and 93 and are imputed by interpolation.

measures to capture the timing and location of the origin of the invention.

It is unlikely that the tort law changes that we exploit in the paper are driven by, or systematically correlated with, trends in medical device innovation for the following reasons. First, as described in Currie and MacLeod (2008), there is little evidence that tort laws were passed in response to specific developments in the health sector, and most laws apply to all torts. Priest (1987) argues that an important driver of early tort reforms was a doctrinal change in the interpretation of tort law, leading some courts to increase injury compensations substantially. Moreover, a number of more recent tort reforms were influenced by the extensive media coverage of the 1992 Liebeck v. McDonald's Restaurants case, in which a woman was awarded more than two million dollars when she accidentally spilled hot coffee in her lap. Finally, it is important to note that our data also include instances in which state courts overturned laws because of constitutionality issues.[13]

Our paper focuses on the demand channel of liability risks (that is, changes in malpractice liability risks affect physicians' demand for new technologies) instead of the direct effect of product liability risk on manufacturers for the following reasons. First, the product liability risk channel is too narrow to capture the phenomenon in our context. For example, technologies that are demanded for defensive reasons (e.g., diagnostic and monitoring technologies; devices aiding smooth delivery under unusual scenarios of cesarean sections; or a small diameter steerable guidewire for use in procedures in narrow arteries) are unlikely to be targets of liability claims themselves, rendering the product-liability channel irrelevant. Second, unlike many other sectors, medical devices are subject to federal regulation. Specifically, the Medical Device Amendments to the Federal Food and Drug and Cosmetic Act passed in 1976 provided pathways for devices approved by the FDA, especially the stringent Pre-Market Approval (PMA) process, to preempt state tort laws (Bivans, 1995). This also implies that changes in state tort laws exploited in this paper are less likely to affect manufacturers through product liability costs in many situations than through their impact on downstream users.

The class of tort reforms central to our empirical analysis is the introduction of caps on non-economic damages—i.e., damages other than monetary losses, such as pain and sufferings. As discussed in Avraham et al. (2012), these damages comprise a substantial fraction of total

[13] Moreover, Deng and Zanjani (2015) do not find evidence of an influence of private interest groups - such as doctors or insurance industry professionals - on tort reform adoption. Similarly, Avraham and Schanzenbach (2015) exploit a detailed dataset of patients experiencing heart attacks and show that passages of tort reforms do not appear correlated with pre-existing trends in treatment intensity.

awards and have often been the main focus of tort reform advocates. Consistent with the literature, we capture tort reforms using a dummy variable, *Damage Caps*, which equals one if caps on non-economic damages are in place. We also control for other (less common) tort reforms, such as caps on punitive damages or changes in the joint-and-several liability rules.

During our sample period, 25 states experienced changes in caps on non-economic damages. Of these states, 16 switched from no caps to a cap, whereas the remaining nine states experienced multiple shifts (e.g., caps were instituted and then rescinded, and in some cases, reinstated). About half of the reforms took place in the late 1980s. In terms of 1985 population and gross state product, the states in which caps on damages were not implemented for the entire sample period are not statistically different from states in which caps were present in some years. The complete list of tort reforms is provided in online appendix Table A1.

Table 1 provides summary statistics. Caps on non-economic damages were present in about 34 percent of the state-year observations of our sample. On average, inventors in a state applied for roughly 1,700 patents (eventually granted) per year, and about 100 of these patents were classified by the USPTO in one of the medical device technology classes. The number of medical patents varies substantially across states. Specifically, the 25th, 50th and 75th percentiles of the median number of patents for a state are, respectively, 9, 37, and 112. Within-state variation (the standard deviation is 186) is much smaller than cross-state variation (the standard deviation is 99).

Online appendix Figure A1 illustrates the growth differential in medical device patenting between states experiencing changes in damage caps during our sample period and those not experiencing any changes. Plots of the absolute number of patents and the ratio between reforming and non-reforming states suggest that patenting grows faster in states without tort reforms. The two groups start to diverge substantially a few years after the first wave of reforms that took place in 1987-1989 and involved some relatively large states. This figure provides a first look at our main result. We now turn to regression analysis to control for other factors that might also contribute to the differential growth rates between the two groups of states.

4.1 Econometric specification

Our baseline specification focuses on the relationship between measures of innovative activities Y_{jt} in state j and period t and the indicator for the presence of caps on non-economic damages:

$$\log Y_{jt} = \beta \text{Damage Caps}_{jt} + \lambda' X_{jt} + \theta_t + \mu_j + zeropat_{jt} + \varepsilon_{jt}, \tag{3}$$

where X_{jt} is a vector of control variables, and μ_j and θ_t are, respectively, the state and year fixed effects. The coefficient β captures the effect of tort reforms on patenting in the state: for example, $\beta < 0$ means that innovators located in a state reduce their patent applications when damage caps are in place. We cluster the standard errors at the state level for all regressions.

It is common in the economics of innovation literature to exploit logarithmic models because the distribution of patenting is highly skewed, which is also the case in our sample (the mean is 98.8, while the median is 29). We include a dummy control variable, $zeropat_{jt}$, for observations where the state has zero patents in the year.[14]

Our identification comes primarily from changes in damage caps over time within a state. The controls X_{jt} and state effects μ_j, therefore, play an important role in our analysis. As discussed previously, there is little evidence that the tort reforms used in our analysis are driven by, or systematically correlated with, trends in medical device innovation. Nonetheless, we perform several robustness checks designed to check pre-trends, placate remaining endogeneity concerns, and to isolate potential confounding factors.

5 Baseline empirical results

In this section, we report the overall effects of non-economic damage caps on patent applications in the medical device fields. In the next section, we explore the heterogeneity in the data to further test the predictions of our model. The regressions in Table 2 show a strong negative correlation between medical device patenting by innovators located in the state and the presence of caps on non-economic damages. All the specifications include year and state effects. These results are consistent with the idea that in the absence of tort reforms, the defensive-adoption effect of high liabilities dominates the chilling effect, on average.

Column 1 presents the estimates of an OLS regression with the number of medical patents as the dependent variable. The coefficient implies an average reduction of roughly 30 patents in years in which damage caps are present. Column 2 shows that the results are similar using log of patents as the dependent variable. Exponentiation of the coefficient implies that in periods when caps on damages are in place, patenting is reduced by roughly 14 percent. Evaluated at the median level of patenting for state-years without damage caps (i.e., 28 patents), this effect

[14] We add one to the number of patents to be able to include state-year observations with no patenting. However, this correction has essentially no impact on our estimates because there are only 18 state-year observations with zero patents.

is equivalent to a reduction of roughly four medical device patents per year.[15]

In column 3, we show that results are not affected if we introduce a variety of controls: lagged total patenting, population, and the number of physicians in a state. Column 4 controls for other changes in tort law: cap on punitive damages, modifications of the collateral-source rule, and modifications of the joint-and-several liability rule. The coefficients of these dummies are all statistically insignificant and small in magnitude, confirming the predominance of non-economic damages. Finally, column 5 shows that results are robust to excluding from the sample states for which caps on non-economic damages pertained only to medical malpractice rather than to torts more generally. This helps to address the concern that the effects might be driven by legislation passed in response to specific incidents of medical malpractice.[16]

Considering the nature of the outcome variable we study, it is plausible that the long term effect of the policy is also driven by a combination of factors that may respond to the short-term changes in innovation activities triggered by tort reforms. For example, initial changes in innovation intensity, firm-size distribution, or technological diversity may, in turn, induce local governments to implement additional growth policies that will drive subsequent research investments (Agrawal et al., 2014). Thus, our estimates need to be interpreted as measuring the net effect of tort reform on innovation after allowing for such endogenous policy changes at the state level or other changes due to private responses. For example, if state governments in control states respond to greater patenting by implementing complementary policies that encourage investments, our estimates would be an upper-bound of the effect of tort reform holding constant subsequent policy changes in other states.[17]

5.1 Robustness of the baseline specification

We perform a variety of robustness tests to confirm our main finding. First, there is the concern that our regressions ignore the count nature of our dependent variable. To address this issue, in column 1 of Table 3 we show that our results are robust to estimating the effect of damages

[15] The difference between the average effect presented in column 1 and the effect evaluated at the median is likely due to the skeweness in the distribution of patenting across state-years.

[16] Currie and Macleod (2008) identify these states as Montana, Nevada and Alaska.

[17] The magnitude of the overall effect of 15 percent is large, though it is in line with the range found in the literature on the impacts of various policies either directly or indirectly targeted at innovation investments. Moreover, our empirical model estimates the impact of tort reforms on the flow of new medical device patent applications per year in a state. Following the approach in Moretti and Wilson (2017), we calculate the implied effect on the stock of medical device patents and we find that tort reforms reduce the stock of patents in a state by 1.7 percent per-year.

caps using a Poisson regression model with fixed effects.

We also examine whether our results are robust to: (i) excluding the five states with the largest number of medical device patents in 1984; and (ii) dropping the ten largest patentees over our sample period. The regressions reported in columns 2 and 3 of Table 3 indicate that the estimated effect is not driven by the largest states nor the largest firms. These findings mitigate a number of concerns over confounding factors (e.g., large patenting firms happen to be located in control states or large control states happen to have implemented pro-innovation policies).

In column 4 of Table 3, we present a placebo test that estimates our baseline model using the sample of non-medical measuring and testing instruments (USPTO class 073), which are unlikely to be affected by liability concerns. The estimated coefficient is statistically insignificant and small in magnitude, suggesting that tort reforms have not affected patenting in this technological field. This finding also helps to address the concern that the impact of damage caps on medical device patenting may reflect omitted variables (e.g., state innovation policies) correlated with tort reforms.

There is also the concern that shifts in political preferences may at the same time drive tort reforms and affect innovation incentives. To address this concern, column 5 of Table 3 includes an additional control capturing Republican-controlled legislatures. Specifically, we exploit data on state legislators and governors from Klaner (2013) to generate a dummy variable equal to one for state years in which state senate, house/assembly and governor are all Republican. This Republican control measure is negatively correlated with medical device patenting, but our estimate of the impact of tort reforms is robust.

We also estimated our baseline regression including state-specific time trends for all 50 states. In this specification, the coefficient on damage caps is not statistically significant, though still negative. This result is consistent with the findings of Meer and West (2013) who show that research designs incorporating state-specific time trends are prone to erroneously estimated null effects of policies when the effects are expected to unfold dynamically. Despite the potential downward bias, our estimates are robust to exploiting less demanding specifications in which state-specific trends are included only for a subset of states. Column 6 of Table 3 illustrates this by introducing state-specific time trends for the ten largest states in terms of patenting.

Online appendix Table A2 provides additional robustness tests. First, it shows that the results are similar when we allow for dynamics and use a multiplicative feedback model that

controls for the logarithm of lagged patenting in medical instruments. Second, it extends our baseline model to include additional controls for gross state products (GSP), the percentage of the state's population with medical insurance coverage, and the percentage with private medical insurance. These variables are proxies for the demand for new medical technologies in a state, and their inclusion reduces the concern that tort reforms are correlated with other unobservable demand shocks affecting innovation. The coefficient on tort reform is stable, and the coefficients of the insurance variables are small and statistically insignificant.[18] Third, it shows that our result is robust to using the (logarithm of the) ratio of medical patents per population as the dependent variable in a weighted regression, with each observation weighted by the square root of the population in the state in 1981 (an approach suggested by Ruhm, 2000). Finally, in unreported regressions we also confirm that our results are robust to including a control, constructed by Frakes (2013), for the adoption of rules requiring physicians to follow national, as opposed to local, standards.[19]

5.2 Extensions of the baseline model

This section summarizes two extensions that are of independent interest. Details of these results are presented in the online Appendices.

Timing of the effect

To explore the timing of the effect, we run a series of regressions with leads and lags of the tort reforms. Online appendix Table A3 illustrates the time path of the impact of tort reform on innovation. We consider treated states that switch only once from no-cap to caps and states with no changes on damage caps for the entire sample period as the control group. For the treated states, we include observations three years before the switch and nine years afterwards. The estimates confirm the negative effect of tort reform on patenting. The coefficients become large and statistically significant three years after the implementation of the caps and stabilize afterwards. We also confirm this finding by including dummies for the years before the reform.

[18] The insurance variables are obtained from the US census, which only reports data for the period 1987-2005. We extrapolate the time series to construct the data for the two missing years.

[19] The coefficient on tort reform is stable, whereas the dummy on national standardization is negative, small and insignificant. A priori, it is not clear how standardization of physician practice may impact innovation incentives, because it may combine a positive demand effect for devices used in national standard procedures, and a negative impact for devices employed in local procedures which deviates from the standard.

The pre-trend dummies have small coefficients, which bounce around the year immediately before the reform, and are statistically insignificant. This suggests that patenting did not start declining before the reform. Overall, this pattern is compatible with a story of innovators slowly reducing their propensity to patent after a tort reform is implemented.

In online appendix 2, we use the synthetic control method by Abadie et al. (2010) as an alternative methodology to explore the timing of the effect. For each treated state that transitioned from no cap to adopting a cap, a 'control state' is constructed through a data-driven procedure that aims to reproduce the counterfactual trajectory in the absence of a tort reform and not simply average across non-reforming states. The results show that the average effect is driven by large treated states. In these states, patenting decreases relative to the constructed controls after the tort reforms and the magnitude of the decline increases over time.

Localized nature of the effect

Our empirical analysis thus far has assumed that the impact of state tort reforms on innovation is localized—i.e., it affects innovators only in states with policy changes. The reader may worry that innovators might respond to policy and demand changes beyond the state boundaries. In online appendix 3, we explicitly examine the impact of tort reforms outside the state in which they are implemented. The results suggest that such effect is limited.

Specifically, we first include an explanatory variable that captures tort reforms in other states. The weights used for these non-local reforms take into account both the demand for specific categories of medical devices in those states and the innovation supply across these categories in the focal state. The regressions (reported in Table A5) show that tort reforms in other states have a very small and statistically insignificant impact on medical device patenting in the focal state. Second, we examine whether the effect of tort reforms in other states depends on the geographic distance between states. The estimates (also reported in Table A5) suggest that only reforms taking place within 500kms have a negative and marginally significant effect on patenting of the focal state, whereas reforms farther away have no effect. Third, in Table A6 we exploit the location of the inventors citing a patent and show that tort reforms have a large and negative impact on patents which have a very local impact on subsequent technologies (i.e., predominately cited by same-state innovators), but no effect on patents involving technologies that spur more distant follow-on knowledge (i.e., predominantly cited by out-of-state innovators). Finally, also in Table A6, we distinguish between patents

from the largest patentees in our sample and patents by smaller innovators who are more likely to rely on local market demand. We find no evidence of an effect on the largest firms and a negative and significant impact on patenting by smaller innovators.

Overall, the empirical evidence suggests that the effect of state tort reforms on medical device innovation is concentrated among local innovators. Various features of the medical device industry may explain this finding. Notably, the management literature (Shaw, 1985; von Hippel, 2006, Chatterji et al., 2008) has documented that user-driven innovation is pervasive in the medical device industry, and that the preferences and needs of practicing physicians often lead them to develop new technologies. This may partly explain the local nature of our result because tort reforms may change physicians' own patenting behaviors as well as their propensity to provide feedback to local innovators with whom they maintain closer interactions. Intuitively, we expect the direct effect on physician innovators to be greater than the indirect effect through informational feedback. To examine this issue empirically, in Table A7 we exploit data from Chatterji et al. (2008) and contrast the effect of tort reforms for patents involving practicing physicians as inventors and other patents. The results are consistent with our expectation: the negative impact of tort reforms is large in magnitude and statistically significant for patents involving physicians, whereas the effect on patents without physicians as inventors is of a smaller magnitude and statistically insignificant.

In addition to extensive user involvement, there are other features of the medical device industry that may explain the local nature of the effect. First, new devices are often incremental advances rather than radically different technologies, and frequently represent the solution of engineering problems which do not require large investments in basic science. Second, many modern medical devices are complex technologies in which a single product is covered by numerous patents linked to different components and design features of the instruments. Together, these features make it plausible for even moderate changes in local market demand to lead to new patents, especially if changes in demand are associated with stronger preferences for particular features of the instruments or for complementary tools that doctors can use both for procedures induced by tort reform and for infra-marginal procedures.

6 Heterogeneous effects

Our baseline analysis has documented an average negative effect of tort reforms on medical device patenting. In this section, we examine the heterogeneity in the effect by (1) the extent

of malpractice risk of a particular medical field and (2) the quality of an invention.

6.1 Malpractice risk and innovation incentives

The model predicts that the impact of tort reforms is more likely to be negative in technology fields characterized by frequent malpractice risk (i.e., high r_O). Intuitively, in these fields, it is likely that physicians adopt new technologies mainly to manage liability risk. Thus, if caps on damages are implemented, the incentives to use these technologies decline and, thus, reduce the overall innovation incentives.

Jena et al. (2011) study US malpractice data from 1991 through 2005. They show that the proportion of physicians facing litigation risk varies substantially across medical specialities. The likelihood of facing a malpractice claim is the largest in surgery (especially neurosurgery and thoracic-cardiovascular surgery) and orthopedics, where the annual probability of facing a claim is about 20 percent. Conversely, malpractice claims are not frequent in specialities such as psychiatry, optics or dentistry, where the annual probability of a claim is below 3 percent. Building on these findings, we exploit the detailed USPTO patent classification system and identify medical instrument patents related to four technology fields: surgical, orthopedics, optics, and dental.[20]

Table 4 provides the estimates for the effect of tort reforms on patenting in each of these four fields. As our model predicts, there is a large negative effect on medical instrument patenting related to specialities in which the frequency of malpractice claims is high (surgery and orthopedics). Conversely, the effect is small and statistically insignificant for patenting associated with specialities with fewer malpractice claims (dental and optics). While we cannot reject that the effects on surgical and orthopedic devices have the same magnitude ($p = 0.97$), we can strongly reject that the effect for surgery is equal to the effect for optics ($p < 0.01$) or to the effect for dental ($p < 0.01$).

6.2 Tort reform and innovation quality

The welfare interpretation of the average decline in innovation would be very different depending on whether it affects high-quality patents or marginal patents with limited impact. To unbundle the heterogeneous effects of tort reforms across different quality levels, we exploit information

[20] We use the following 3-digit classes: 128 and 600-607 for surgical; 433 for dental; 351 and 356 for optics; and various sub-classes of class 623 for orthopedics. Surgery patents are 105,509 (about 78 percent of the sample), there are 2,240 patents in optics (about 2 percent of the sample), 5,414 patents in orthopedics (about 4 percent of the sample) and 6,526 patents in dental (about 5 percent of the sample).

on the citations received by each patent. The economics of innovation literature has often employed the number of citations received by a patent as an indirect measure of patent value (Pakes and Griliches, 1980). Since citation counts are inherently truncated, and levels differ across technology areas, we filter citations by removing grant-year and 3-digit technology class effects. We then identify the (filtered) citation quintile to which each patent belongs.

In Table 5, we present the estimates of our baseline model for each of the quality quintiles, with quintile 1 including patents with the lowest number of citations and quintile 5 the highest. The estimates show a non-monotonic relation between damage caps and patenting across patents of different quintiles. The effect is not statistically significant for patents in the lowest quality quintile. The effect becomes negative and significant in the second quintile, and the magnitude of the negative effect is larger as patent quality increases (with the largest being in the fourth quintile). The effect, again, becomes small and insignificant for patents in the top quality quintile.

We perform a variety of tests to confirm the robustness of this finding. First, we re-estimate the relationship between damage caps and patenting at a finer level of citation deciles. The (unreported) estimates are in line with those from the quintile analysis and show a U-shaped relationship between tort reform and innovation. There is a statically significant negative impact only for patents from the 4th to the 9th deciles, with the largest effect on the 7th decile of the distribution. Second, we confirm that the pattern is robust to using alternative measures of patent quality. In online appendix Table A8, we construct quintile bins exploiting residuals obtained from filtering out grant-year effects, technology effects and the number of claims. This alternative measure—which captures normalized citations per patent claim—yields results very similar to those obtained in Table 5.[21]

Explaining the U-shaped effect

Multiple reasons might account for the non-monotonic impact of tort reforms illustrated in Table 5. In fact, our theoretical model predicts such relationship when we perform comparative statics in b_N, which is the expected effectiveness of the new technology. This result is formally proved when we derive Proposition 2, and it is illustrated in Figure 2.

FIGURE 2 HERE

[21] We also obtain similar results: (i) filtering citations removing only the grant year effects; and (ii) measuring quality with the number of patent claims filtered by 3-digit technology effects.

Intuitively, physicians do not adopt low-quality technologies independent of the malpractice liability regime and, hence, tort reforms have little impact in that quality bin. As the value of a new technology increases and gets closer to the value of the old technology, adoption becomes more likely to mainly manage risk. In this quality bin, the effect of tort reforms on innovation incentives is negative because the physician's willingness to pay for a safer technology decreases after the reform. For new technologies with value greater than the old technology, tort reform has two opposing effects: It decreases innovation incentives for safer devices, but increases innovation incentives for riskier devices. Furthermore, the positive effect of the reform gets stronger than its negative effect as the value of the new technologies becomes higher. This explains why the negative effect of tort reform is mitigated at higher quality bins and we find an insignificant effect for patents of the highest quality.

Note that the above comparative statics is with respect to b_N, which is the expected effectiveness of the new technology. While it is likely that the lowest quintile of the citation distribution captures innovations with low b_N and that patents in the top quintile capture technologies with large b_N, intermediate quintiles may contain technologies with mixed levels of b_N and r_N. To empirically disentangle b_N from r_N is very challenging with our data, and citations are one of the few quality measures that are available for a variety of different medical technologies. Despite the presence of such measurement error, the estimates are consistent with the model's prediction, suggesting that citations may be a reasonable proxy for b_N.

Finally, we perform additional tests of the model exploiting the fact that in the U.S. medical devices are subject to the FDA regulatory process.[22] One of the FDA's regulatory pathways to bring a device to market is the Pre-market Approval (PMA) process, which requires detailed evidence for product effectiveness and safety from clinical trials (Stern, 2015). The FDA requests PMAs for devices that are used to support or sustain human life, are of substantial importance in preventing impairment of human health, or which present a potential, unreasonable risk of illness or injury. Furthermore, the expenditure required to complete PMAs is substantial (an average of 75 million dollar per device according to survey evidence in Makower et al., 2010). Thus, data on PMAs may provide a reasonable window on technologies with high b_N, high r_N, or both. Our theoretical framework suggests that tort reforms will have

[22] Two qualifications about FDA device data are worthwhile mentioning. First, FDA applicants are often device manufacturers that are not necessarily the initial inventors. Second, there is evidence of strategic delays in the introduction of medical devices in the U.S. market relative to the European markets (Grennan and Town, 2015). Both of these issues may generate substantial measurement errors for innovative activities and geographic locations and, hence, bias the coefficients toward zero.

little or even positive impact on innovation incentives for these devices.

Using PMA applications as a measure of innovation, we estimate the impact of tort reforms using the same method as in our baseline results. The average effect is small and insignificant. Considering that these devices are likely to be of high value, the overall small effect is consistent with what we find for patents with the most citations. Split-sample analysis shows that the estimated effect is largely negative for medical specialties characterized by high liability risks and largely positive for medical specialties with low liability risks, though the magnitude and statistical significance vary by specifications.[23] However, the difference in the estimated effects between high-risk and low-risk fields is sizable and statistically significant across different specifications.[24] This difference is also consistent with the heterogeneous effects by liability risk obtained using patent data.

7 Conclusions

This paper investigates how tort reforms affect the development of new medical device technologies by exploiting state tort reforms and patent data. We develop a theoretical model in which tort reforms increase physicians' propensity to adopt riskier technologies because these reforms mitigate the "chilling effect" of high liabilities. At the same time, we show that tort reforms also reduce physicians' propensity to defensively adopt low-risk technologies that reduce the probability of malpractice disputes, even when their expected benefit is limited. These shifts in technology adoption affect upstream R&D investments, and the overall impact on the development of new technologies depends on the relative strengths of the two effects.

Our empirical analysis shows that tort reform is associated with an average decline in patenting, though the effect is highly heterogeneous. Specifically, the decline appears concentrated in technology areas related to medical specialties with high frequency of malpractice claims. Moreover, the effect is predominantly driven by patents of intermediate quality, and not by technologies of the highest or lowest value. These heterogeneous results are consistent with the predictions of the theoretical model.

[23] Based on Jena et al. (2011), we define specialties with high liability risk as anesthesiology, cardiovascular, general and plastic surgery, neurology, obstetrical and gynecological, orthopedic, and radiology. Other fields are defined as specialties with low liability risk.

[24] For example, in the specification equivalent to column 2 of Table 2, the average effect of tort reform is 0.002 (std. err. = 0.016) counting all PMA applications. The estimated coefficient is -0.01 (0.008) when counting PMA applications only in specialties with high liability risks, and 0.031 (0.014) for specialties with low liability risks. The difference in the estimated effects between the two subsamples is statistically significant at the 1% level.

A common view in academic and policy debates is that 'liability retards innovation.' Our analysis shows that the link between liability and innovation is complex and nuanced. The finding of a significant negative average effect of tort reforms on patenting suggests that the chilling effect of high liabilities does not have a strong empirical support. This is because this simple view ignores the potential encouraging effect of high liabilities on innovations that help physicians manage risks, which may be suppressed by tort reforms. This interpretation is further corroborated by the finding that the average result is driven by fields in which physicians report concerns over malpractice litigation and pressure to practice defensive medicine.

The large decline in innovation, which appears to be mostly for defensive purpose, may translate to only moderate welfare loss. In particular, tort reforms do not seem to affect the development of the most cited patents, which are typically associated with large private and social value (Pakes and Griliches, 1980). Additional support for this welfare interpretation is obtained when we combine our results with health economics research documenting that tort reforms affect physician behaviors, but do not have large effects on measurable health outcomes (Avraham and Schanzenbach, 2015; Frakes and Jena, 2016; Kessler, 2011). A more comprehensive welfare assessment, however, would require a more structural analysis of the value of safer technologies versus riskier, but potentially more effective, technologies to physicians and to patients, as well as the spillover effects of these technologies to follow-on innovations as well as to other sectors of the economy.

More broadly, our paper provides empirical evidence that tort reforms can affect the rate and the direction of technological change, indicating that these policies have dynamic effects on innovation incentives that go beyond their short-term impact on patients and health costs. As Finkelstein (2004) stresses, recognizing and estimating these dynamic effects is crucial to evaluating the costs and benefits of policy reforms.

References

[1] Abadie, Alberto, Alexis Diamond, and Jens Hainmueller (2010), "Synthetic control methods for comparative case studies: Estimating the effect of California's tobacco control program," *Journal of the American Statistical Association* 105: 493-505

[2] Acemoglu, Daron (1998) "Why do new technologies complement skills? Directed technical change and wage inequality," *Quarterly Journal of Economics* 113: 1055-1089

[3] Acemoglu, Daron, David Cutler, Amy Finkelstein, and Joshua Linn (2006), "Did Medicare Induce Pharmaceutical Innovation?," *American Economic Review* 96: 103-107

[4] Acemoglu, Daron and Joshua Linn (2004), "Market Size in Innovation: Theory and Evidence from the Pharmaceutical Industry," *Quarterly Journal of Economics* 119: 1049-1090

[5] Aghion, Philippe, Antoine Dechezleprêtre, David Hemous, Ralf Martin, and John Van Reenen (2015), "Carbon taxes, path dependency and directed technical change: evidence from the auto industry," *Journal of Political Economy*, forthcoming

[6] Agrawal, Ajay, Iain Cockburn, Alberto Galasso, and Alexander Oettl (2014) "Why are some regions more innovative than others? The role of small firms in the presence of large labs," *Journal of Urban Economics* 81: 149-165

[7] Avraham, Ronen (2007), "An empirical study of the impact of tort reforms on medical malpractice settlement payments," *Journal of Legal Studies* 36: 183–229.

[8] Avraham, Ronen, Leemore S. Dafny and Max M. Schanzenbach (2012), "The impact of tort reform on employer-sponsored health insurance premiums," *Journal of Law, Economics, and Organization* 28: 657-686

[9] Avraham, Ronen and Max Schanzenbach (2015), "The impact of tort reform on intensity of treatment: Evidence from heart patients," *Journal of Health Economics* 39: 273-288

[10] Barker, Drucilla (1992), "The Effects of Tort Reform on Medical Malpractice Insurance Markets: An Empirical Analysis," *Journal of Health Politics, Policy and Law* 17: 143-161.

[11] Bivans, Roger (1995), "Substantially Equivalent Federal Preemption of State Common-Law Claims Involving Medical Devices," *Texas Law Review* 74: 1087-1095

[12] Blume-Kohout, Margaret and Neraj Sood (2013), "Market Size and Innovation: Effects of Medicare Part D on Pharmaceutical Research and Development," *Journal of Public Economics* 97: 327-336

[13] Budish, Eric, Benjamin Roin and Heidi Williams (2015), "Do Firms Underinvest in Long-Term Research? Evidence from Cancer Clinical Trials," *American Economic Review,* 105: 2044-2085

[14] Chatterji, Aaron, Kira Fabrizio, Will Mitchell and Kevin Schulman (2008), "Physician-industry cooperation in the medical device industry," *Health Affairs* 27: 1532-1543

[15] Chatterji, Aaron, Kira Fabrizio (2014), "Using users: When does external knowledge enhance corporate product innovation?," *Strategic Management Journal* 35: 1427-1445

[16] Clemens, Jeffrey (2013), "The effect of U.S. health insurance expansion on medical innovation," NBER working paper 19761

[17] Currie, Janet and Bentley MacLeod (2008), "First Do No Harm? Tort Reform and Birth Outcomes," *Quarterly Journal of Economics* 123: 795-830

[18] Danzon, Patricia (1984), "The Frequency and Severity of Medical Malpractice Claims," *Journal of Law and Economics* 17: 115-148.

[19] Deng, Yiling and George Zanjani (2015), "What Drives Tort Reform Legislation? Economics and Politics of the State Decisions to Restrict Liability Torts," working paper

[20] Finkelstein, Amy (2004), "Static and dynamic effects of health policy: Evidence from the vaccine industry," *Quarterly Journal of Economics* 119, 527-564

[21] Frakes, Michael (2013), "The Impact of Medical Liability Standards on Regional Variations in Physician Behavior: Evidence from the Adoption of National-Standard Rules," *American Economic Review* 103: 257-276

[22] Frakes, Michael (2015) "The surprising relevance of medical malpractice law," *University of Chicago Law Review*: 317-391

[23] Frakes, Michael and Jena Anupam (2016), "Does Medical Malpractice Law Improve Health Care Quality?," *Journal of Public Economics*, forthcoming.

[24] Greenberg, Michael (2009), "Medical Malpractice and New Devices: Defining an Elusive Standard of Care," *Health Matrix* 19: 423-45

[25] Grennan, Matthew and Robert Town (2015), "Regulating Innovation with Uncertain Quality: Information, Risk, and Access in Medical Devices," working paper

[26] Jaffe, Adam and Karen Palmer (1997), "Environmental Regulation And Innovation: A Panel Data Study," *Review of Economics and Statistics* 79: 610-619

[27] Jena, Anupam, Seth Seabury, Darius Lakdawalla and Amitabh Chandra (2011), "Malpractice risk according to physician specialty," *New England Journal of Medicine* 365: 629-636

[28] Kessler, Daniel (2011), "Evaluating the Medical Malpractice System and Options for Reform," *Journal of Economic Perspectives* 25: 93–110.

[29] Kessler, Daniel and Mark McClellan (1996), "Do Doctors Practice Defensive Medicine?," *Quarterly Journal of Economics* 111: 353-390

[30] Makower, Josh, Aabed Meer and Lyn Denend (2010), "FDA impact of us medical technology innovation: A survey of over 200 medical technology companies," Stanford University Report

[31] Meer, Jonathan, and Jeremy West (2013), "Effects of the Minimum Wage on Employment Dynamics," NBER working paper 19262

[32] Moretti, Enrico, and Daniel Wilson (2017) "The effect of state taxes on the geographical location of top earners: evidence from star scientists," *American Economic Review*, forthcoming

[33] Nistor Christina and Catherine Tucker (2015), "Third-Party Certification: The Case of Medical Devices," working paper

[34] Pakes, Ariel and Zvi Griliches (1980), "Patents and R&D at the firm level: A first report," *Economics Letters* 5: 377-381

[35] Parchomovsky, Gideon and Alex Stein (2008), "Torts and Innovation," *Michigan Law Review* 107: 285-315

[36] Priest, George (1987), "The current insurance crisis and modern tort law," *Yale Law Journal* 96: 1521-1590

[37] Priest, George (2011), "The Effects of Modern Tort Law on Innovation and Economic Growth," in *Rules for Growth*, the Kauffman Task Force on Law, Innovation, and Growth

[38] Ruhm, Christopher (2000) "Are recessions good for your health?" *Quarterly journal of economics* 115: 617-650

[39] Scotchmer, Suzanne (1999), "On the optimality of the patent renewal system," *RAND Journal of Economics* 30: 181-196

[40] Seabury, Seth, Amitabh Chandra, Darius Lakdawalla, and Anupam B. Jena (2013) "On average, physicians spend nearly 11 percent of their 40-year careers with an open, unresolved malpractice claim," *Health Affairs* 32: 111-119

[41] Shaw, Brian (1985), "The role of the interaction between the user and the manufacturer in medical equipment innovation," *R&D Management* 15: 283-292

[42] Shurtz, Ity (2014), "Malpractice Law, Physicians' Financial Incentives, and Medical Treatment: How Do They Interact?," *Journal of Law and Economics* 57: 1-29

[43] Stern, Ariel (2015), "Innovation under Regulatory Uncertainty: Evidence from Medical Technology," working paper

[44] Viscusi, Kip and Michael Moore (1993), "Product liability, research and development, and innovation," *Journal of Political Economy* 101: 161-184

[45] Viscusi, Kip, and Patricia Born (1995), "Medical Malpractice Insurance in the Wake of Liability Reform," *Journal of Legal Studies* 24: 463-490.

[46] Von Hippel, Eric (2006) "Democratizing Innovation," MIT Press Books, Cambridge MA.

[47] Weyl, Glenn and Jean Tirole (2012), "Market Power Screens Willingness to Pay," *Quarterly Journal of Economics* 127: 1971-2003

Table 1. Summary statistics

	Obs.	Mean	Std. Dev.	Min	Max
Total Patents	1071	1697.8	3110.4	21	28383
Medical Device Patents	1071	98.8	210.4	0	2070
Damage Caps	1071	0.3	0.5	0	1
Year	1071	1995	6.1	1985	2005
Population (1,000)	1071	5189.2	5753.1	453.5	35827.9
Physicians per 1,000 population	1071	2.3	0.9	1.2	7.9

NOTES: Unit of observation is U.S. state-year. Total Patents is the total number of patents applied for (and eventually granted) in a year in the state. Medical Device Patents are applications classified by the USPTO in one of the medical device patent classes. Damage Caps is equal to one if the state has a cap on non-economic damages. Data on population and physicians are from the US Census and the Bureau of Economic Analysis (BEA).

Table 2. Damage caps and medical device patenting

	(1)	(2)	(3)	(4)	(5)
Dependent Variable	Med Pats$_t$	log(Med Pats$_t$)	log(Med Pats$_t$)	log(Med Pats$_t$)	log(Med Pats$_t$)
Damage Caps$_t$	-29.708**	-0.150**	-0.159***	-0.152***	-0.162**
	(12.52)	(0.06)	(0.06)	(0.06)	(0.07)
log(Population)			1.134***	1.400***	1.094**
			(0.44)	(0.43)	(0.42)
Physicians per 1,000 population			0.130	0.119	0.112
			(0.16)	(0.162)	(0.17)
log(Total Patents$_{t-1}$)			0.045	0.030	0.083
			(0.13)	(0.13)	(0.14)
Punitive Damage Cap				-0.084	
				(0.07)	
Collateral-source rule				0.053	
				(0.09)	
Joint and Separate Liability				-0.030	
				(0.07)	
Year Effects	YES	YES	YES	YES	YES
State Effects	YES	YES	YES	YES	YES
Drop states with malpractice-focused reform					YES
Observations	1071	1071	1071	1071	1008

NOTES: OLS estimation. * significant at 10 percent, ** significant at 5 percent and *** significant at 1 percent. Med Pats = number of patent applications in medical device fields in the state. Damage Caps =1 if a cap on non-economic damages is present in the state. Total Patents = total patent applications in the state. Other reform dummies are indicator variables for cap on punitive damages, modifications of the collateral-source rule and modifications of the joint-and-several liability rule. Robust standard errors clustered at the state level. In columns 2-5, we add 1 to Med Pats and include a dummy that equals one for state-years without patenting.

Table 3. Robustness of baseline specification

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable	Med Pats$_t$	log(Med Pats$_t$)	log(Med Pats$_t$) dropping largest assignees	log(Mesurement Pats$_t$)	log(Med Pats$_t$)	log(Med Pats$_t$)
Estimation Method	Poisson	OLS	OLS	OLS	OLS	OLS
Sample	full	drop largest states	full	full	full	full
Damage Caps$_t$	-0.102**	-0.154***	-0.164***	-0.030	-0.138**	-0.124**
	(0.04)	(0.06)	(0.05)	(0.06)	(0.06)	(0.06)
Republican control					-0.102**	
					(0.05)	
Top 10 states-specific trends	NO	NO	NO	NO	NO	YES
Control variables	YES	YES	YES	YES	YES	YES
Year Effects	YES	YES	YES	YES	YES	YES
State Effects	YES	YES	YES	YES	YES	YES
Observations	1071	966	1071	1071	1050	1071

NOTES: OLS estimation. * significant at 10 percent, ** significant at 5 percent and *** significant at 1 percent. Med Pats = number of patent applications in medical device fields in State. Damage Caps =1 if a cap on non-economic damages is present in the state. Republican control =1 if Republican party controls state house, senate and governor (variable not available for DC). Robust standard errors clustered at the state level. We include a dummy that equals one for state-years with zero patenting. In column 2, we drop states with the largest patenting in medical devices in 1984 (CA, DE, NY, NJ and FL). In column 3, we drop the ten largest patentees in medical instruments over our sample period. In Column 4, we conduct a placebo test using the measuring and testing (patent class 73). Regressions also control for lagged total patenting, log(Population), and Physicians per 1,000 population.

Table 4. Damage caps and litigation risk

	(1)	(2)	(3)	(4)
Dependent Variable	log(Med Pats$_t$) in surgery	log(Med Pats$_t$) in orthopedics	log(Med Pats$_t$) in optics	log(Med Pats$_t$) in dentistry
Damage Caps$_t$	-0.190***	-0.189**	-0.013	0.058
	(0.05)	(0.08)	(0.04)	(0.06)
Control variables	YES	YES	YES	YES
Year Effects	YES	YES	YES	YES
State Effects	YES	YES	YES	YES
Observations	1071	1071	1071	1071
Sample Mean of Med Pats	78.09	3.89	1.19	4.66

NOTES: OLS estimation. * significant at 10 percent, ** significant at 5 percent and *** significant at 1 percent. Med Pats = number of patent applications in medical device fields in the state. Damage Caps =1 if a cap on non-economic damages is present in the state. Robust standard errors clustered at the state level. We add 1 to Med Pats to include state-years with no patenting. Regressions control for lagged total patenting, log(Population), Physicians per 1,000 population, and a dummy that equals one for state-year without patenting.

Table 5. Damage caps and patent quality

	(1)	(2)	(3)	(4)	(5)
Dependent Variable	log(Med Pats$_t$) in 1st citation quintile	log(Med Pats$_t$) in 2nd citation quintile	log(Med Pats$_t$) in 3rd citation quintile	log(Med Pats$_t$) in 4th citation quintile	log(Med Pats$_t$) in 5th citation quintile
Damage Caps$_t$	0.141	-0.186**	-0.278***	-0.370***	-0.089
	(0.10)	(0.07)	(0.08)	(0.07)	(0.06)
Control variables	YES	YES	YES	YES	YES
Year Effects	YES	YES	YES	YES	YES
State Effects	YES	YES	YES	YES	YES
Observations	1071	1071	1071	1071	1071

NOTES: OLS estimation. * significant at 10 percent, ** significant at 5 percent and *** significant at 1 percent. Med Pats = number of patent applications in medical device fields in the state. Damage Caps =1 if a cap on non-economic damages is present in the state. Citations quintiles constructed from citations filtered by grant-year and technology-class effects. Robust standard errors clustered at the state level. We add 1 to Med Pats to include state-years with no patenting. Regressions control for lagged total patenting, log(Population), Physicians per 1,000 population, and a dummy that equals one for state-years without patenting. Higher quintiles correspond to patents receiving more citations.

Figure 1. Tort Reform (reduction in *H*) and technology adoption

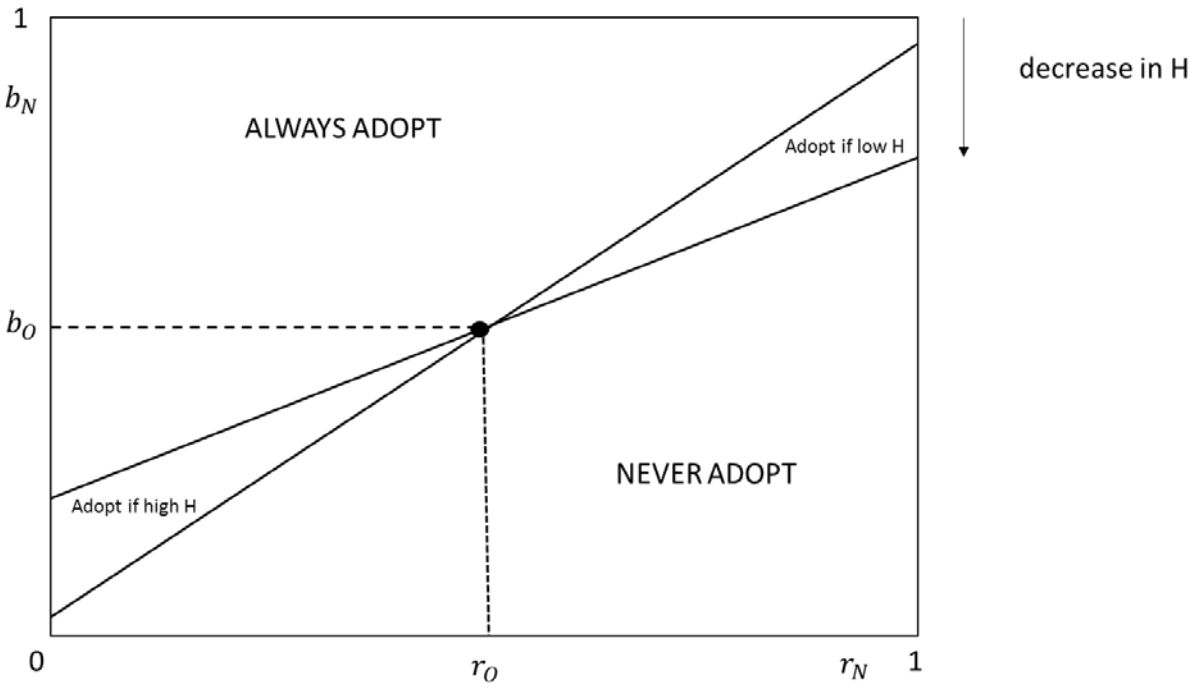

Figure 2. Effect of a reduction in *H* on innovation intensity as a function of b_N given different levels of r_0