

The Ecology of Defensive Medicine and Malpractice Litigation

Angelo Antoci^a, Alessandro Fiori Maccioni^{a,*}, Paolo Russu^a

^a*Department of Economics and Business
University of Sassari Via Muroni 25, 07100 Sassari, Italy*

Abstract

We analyse the relations between defensive medicine and medical malpractice litigation by an evolutionary game between physicians and patients. When medical treatment fails, patients may sue the physician and seek compensation. Conversely, physicians may prevent negligence charges by practising defensive medicine. We study the population dynamics and find the Nash equilibria and their Pareto-ranking. Furthermore, we show that, when the mixed-strategy equilibrium exists, then the shares of defensive physicians and litigious patients exhibit time-evolution paths similar to prey-predator relations in the Lotka-Volterra model, in which physicians can be seen as preys and litigious patients as their predators. Then, defensive physicians can be seen as adapted preys who improved their Darwinian fitness through mutation. The increase in adapted preys (*i.e.* defensive physicians) decreases predators' fitness leading to a decrease in predators (*i.e.* litigious patients). In this context, we show that perfect cooperation with neither defensive physicians nor litigious patients can be the social first best. Our results may explain heterogeneous findings in empirical literature on these phenomena.

Keywords: Defensive medicine; malpractice litigation; clinical risk; legal risk; predator-prey model; evolutionary game.

1. Introduction

Medical malpractice litigation may be as old as medicine. However, it has got the attention of economic research only in the early 1970s, when prices of malpractice insurance reached record highs because of relevant increases in lawsuits. Defensive medicine is the practice performed by healthcare providers to safeguard themselves from patients' claims, while disregarding improvements in patients' health (Tancredi and Barondess, 1978; Kessler and McClellan, 1996). Through defensive medicine, physicians can discourage patients from suing and minimise their chance of being held liable in the event of lawsuits. It takes the form of avoidance behaviour and is called "negative" defensive medicine when the physician refuses to perform high risk procedures. It takes the form of assurance behaviour and is called "positive" defensive medicine when it is performed through extra tests or procedures. Positive defensive medicine can therefore be considered as a particular case of excessive provision of unnecessary care, and is the type that we study in this paper.

Theoretical research often considers the inefficient provision of medical services as a principal-agent problem and describes its market failures due to asymmetric information, moral hazard and conflicts of interest (for early contributions see Arrow, 1963; Pauly, 1968; Zeckhauser, 1970; Pauly, 1980; see also Dionne and Contandriopoulos, 1985; Hammer, Haas-Wilson and Sage, 2001). The literature generally agrees that physicians' behaviour does not perfectly fit the neoclassical theory of firms, because of the following aspects (see also McGuire, 2000). Physicians tend to maximise their profits but may also give up some income to promote patients' welfare. This altruism is consistent

*Corresponding author: Dipartimento di Scienze Economiche e Aziendali, Università di Sassari, Via Muroni 25, 07100 Sassari Italy Tel.+39 079 213016 - Fax +39 079 203002

Email addresses: angelo.antoci@virgilio.it (Angelo Antoci), alex.fiori.maccioni@gmail.com (Alessandro Fiori Maccioni), russu@uniss.it (Paolo Russu)

with the income/leisure tradeoff that determines labour supply in neoclassical microeconomics. The quantity of medical treatment is not directly contractible and can be set by physicians (which decide time and effort) in partial response to self-interest and subject to demand constraints proportional to the benefits of patients. Physicians can encourage unnecessary healthcare to maximise their profits, by increasing their observable effort when treating insured patients (Ma and McGuire, 1997) or by increasing their unobservable effort and observable care to prevent patients from switching to a competitor in case of adverse medical outcomes (Allard, Léger and Rochaix, 2009). This latter over-treatment can be considered a contingent form of positive defensive medicine. Superfluous but profitable therapies are more likely when physicians are less fearful of liability (Currie and MacLeod, 2008). As regards negative defensive medicine, maximising profits can also induce physicians to under-provide services to the high severity patient if they face liability (Ellis and McGuire, 1986; Ma, 1994; Ellis, 1998; Feess, 2012). Physicians can perform defensive medicine also because of fear of reputational losses (Quinn, 1998; Madarász, 2012). Stricter negligence standards can lead to more defensive but less negligent medicine and this response may increase social welfare (Olbrich, 2008; *contra* Gal-Or, 1999).

Researchers generally agree that defensive medical practices are widespread and produce social costs that are not trivial, though not easy to estimate (see among others Kessler and McClellan, 1996; Dubay, Kaestner and Waidmann, 1999, 2002; Fenn, Gray and Rickman, 2004; Studdert et al., 2005; Fenn, Gray and Rickman, 2007; Currie and MacLeod, 2008; Sloan and Shadle, 2009). Medical malpractice claims and the related costs can vary significantly over time and geographically (Robinson, 1986; Black, 1990; Danzon, 1990; Studdert et al., 2000; Kessler, Summerton and Graham, 2006; Rodwin et al., 2008). Empirical evidence indicates that liability system can influence defensive medical practices (Kessler and McClellan, 2002*a,b*; Kessler, 2011; Lakdawalla and Seabury, 2012) and the costs of medical malpractice insurance (Danzon, 1985; Danzon, Pauly and Kington, 1990; Danzon, 1991), but the impact of tort reforms is still theoretically ambiguous (Avraham and Schanzenbach, 2010).

The previous theoretical literature has a gap in explaining the heterogeneous findings of empirical research, outlined above, on the impact assessment of defensive medicine and medical malpractice litigation. We fill this gap by adopting an evolutionary perspective that accounts for the different time dynamics of these phenomena, and by studying the effects of changes in clinical, legal and economic variables. We propose an original bimatrix game, in which patients can choose to litigate or not if injured, and physicians to defend or not against possible liability by means of additional superfluous medical care. The population dynamics result from a series of one-shot encounters between randomly-drawn members of each population. Over time, agents attempt to improve their expected payoffs by imitating successful behaviours; we describe this learning-by-imitation process with the replicator dynamics, a tool widely used in economic literature (see Maynard Smith and Price, 1973; Taylor and Jonker, 1978; Taylor, 1979; Maynard Smith, 1982; Hofbauer and Sigmund, 1988; Fudenberg and Harris, 1992; Bjornerstedt and Weibull, 1993; Kandori, Mailath and Rob, 1993; Hofbauer and Weibull, 1996; Weibull, 1997; Schlag, 1998; Hofbauer and Schlag, 2000; Hauert et al., 2002*a,b*; Hauert and Doebeli, 2004; for a review Ohtsuki and Nowak, 2006).

We find that shares of litigious patients and defensive physicians can be cyclical over time and their average values may be invariant over the cycle. This cyclical evolution resembles predator-prey dynamics in Lotka-Volterra models where litigious patients can be seen as predators and physicians as their preys; then, physicians who perform defensive medicine can be seen as adapted preys who improved their Darwinian fitness through mutation. Surprisingly, neither clinical risk nor defensive costs tend to affect the average share of defensive physicians over the cycle, and the same invariance exists between legal costs and the average share of litigious patients. Finally, we demonstrate that any mixed-strategy equilibrium is always sub-optimal with respect to perfect cooperation with neither defensive physicians nor litigious patients. Perfect cooperation can also be the social first-best when either the harm for patients from defensive medicine is high enough, or the probability of clinical failure is low enough.

Our paper makes an advance in describing the legal, clinical and economic drivers of “positive” defensive medicine and medical malpractice litigation, and can help to explain heterogeneous results of empirical literature on these phenomena. Our results suggest that policy makers should pay attention to the overall underlying dynamics of these phenomena and be cautious when interpreting

their short-term trends, which can be irregular.

2. The Model

We propose an evolutionary game between a population of physicians and a population of patients. In each instant of time $t \in [0, +\infty)$, there is a large number of random pairwise encounters between physicians and patients. In each encounter, a physician provides a health service to a patient. The healthcare process can fail with probability p or reach a desirable outcome with probability $1-p$. If the healthcare process fails, the patient suffers a damage R and can choose, at a cost C_L , to sue the physician for negligence. If winning the case, the patient gets full compensation R from the physician. If losing, the patient must pay K to the physician as reparation for legal and reputation losses.

The outcome of the legal proceedings is uncertain and depends on the medical care previously provided by the physician. The best medical practice costs the physician an effort C_{ND} . The defensive medical practice costs the physician a higher effort $C_D > C_{ND}$, it causes a harm H to the patient and it keeps unchanged the probability of failure p in the healthcare process. In the event of lawsuit, if the physician provided the best medical care, the patient wins with probability q_{ND} and the physician wins with probability $1 - q_{ND}$. Conversely, if the physician provided defensive medicine, the patient wins with probability q_D and the physician wins with probability $1 - q_D$. We assume $q_D < q_{ND}$, that is defensive medicine protects the physician in court.

2.1. The one-shot game

In each instant of time $t \in [0, +\infty)$, a randomly-chosen patient plays a one-shot game with a randomly-chosen physician. The physician can play two pure strategies, D or ND , representing respectively performing defensive medicine or not. The patient can play two pure strategies, L or NL , representing respectively litigating or not in case of medical failure. Each player chooses the strategy without knowing ex ante the other player's choice.

The physician's payoffs of strategies D and ND are:

$$\begin{array}{c|cc}
 & L & NL \\
 \hline
 D & \pi_D^L = -C_D + p [K(1 - q_D) - R q_D] & \pi_D^{NL} = -C_D \\
 \hline
 ND & \pi_{ND}^L = -C_{ND} + p [K(1 - q_{ND}) - R q_{ND}] & \pi_{ND}^{NL} = -C_{ND}
 \end{array} \quad (1)$$

The patient's payoffs of strategies L and NL are:

$$\begin{array}{c|cc}
 & D & ND \\
 \hline
 L & \pi_L^D = -H - p[C_L + (R+K)(1 - q_D)] & \pi_L^{ND} = -p[C_L + (R+K)(1 - q_{ND})] \\
 \hline
 NL & \pi_{NL}^D = -H - R p & \pi_{NL}^{ND} = -R p
 \end{array} \quad (2)$$

The payoff matrices contain the following notation: C_D and C_{ND} are the physician's costs of strategies D and ND , respectively; R is both the patient's damage from failure in the healthcare process and the compensation paid by the physician if the patient wins the lawsuit; K is the compensation paid by the patient if the physician wins the lawsuit; q_D and q_{ND} are the probabilities that the physician loses (and that the patient wins) the lawsuit with physician's strategies D and ND , respectively; H is the patient's harm from defensive medicine; C_L is the patient's cost of litigation. The parameters in the payoff matrices satisfy the conditions: $p, q_D, q_{ND} \in (0, 1)$; $q_{ND} > q_D$; $H, R, K, C_L, C_D, C_{ND} > 0$; $C_D > C_{ND}$.

2.2. Evolutionary dynamics

Let $d(t) \in [0, 1]$ represent the share of physicians adopting strategy D and let $l(t) \in [0, 1]$ represent the share of patients adopting strategy L , at any time t . Consequently, $1 - d(t)$ and $1 - l(t)$ represent, respectively, the shares of physicians playing strategy ND and of patients playing strategy NL .

The physicians' expected payoffs from playing strategies D and ND are:

$$\Pi_D(l) = \pi_D^L l + \pi_D^{NL} (1 - l),$$

$$\Pi_{ND}(l) = \pi_{ND}^L l + \pi_{ND}^{NL} (1 - l),$$

where l and $1 - l$ represent the probabilities that a physician is matched with a patient who plays, respectively, strategy L or NL .

The patients' expected payoffs from playing strategies L and NL are:

$$\Pi_L(d) = \pi_L^D d + \pi_L^{ND} (1 - d),$$

$$\Pi_{NL}(d) = \pi_{NL}^D d + \pi_{NL}^{ND} (1 - d),$$

where d and $1 - d$ represent the probabilities that a patient is matched with a physician who plays, respectively, strategy D or ND .

The average payoffs in the populations of physicians and of patients are:

$$\bar{\Pi}_{PH} = d \Pi_D(l) + (1 - d) \Pi_{ND}(l)$$

$$\bar{\Pi}_{PA} = l \Pi_L(d) + (1 - l) \Pi_{NL}(d)$$

We assume that the time evolution of d and l is described by the standard replicator dynamics, a learning-by-imitation model of evolution widely used in economics (see among others Hofbauer and Sigmund, 1988; Bjornerstedt and Weibull, 1993; Weibull, 1997; Schlag, 1998). The replicator dynamics postulate that players are boundedly rational and update their choices by adopting the relatively more rewarding behaviour that emerges from available observations of others' behaviours. Strategies will grow (decline) the more, the higher (lower) their payoff differential with respect to the population average payoff. Accordingly, in our two-strategy context the dynamic system is:

$$\begin{aligned} \dot{d} &= d [\Pi_D(l) - \bar{\Pi}_{PH}] = d(1 - d) [\Pi_D(l) - \Pi_{ND}(l)] \\ \dot{l} &= l [\Pi_L(d) - \bar{\Pi}_{PA}] = l(1 - l) [\Pi_L(d) - \Pi_{NL}(d)] \end{aligned} \quad (3)$$

where \dot{d} and \dot{l} represent the time derivatives of the shares d and l , respectively. The factors $d(1 - d)$ and $l(1 - l)$ are always non-negative, so the signs of \dot{d} and \dot{l} will depend respectively on the signs of the payoff differentials:

$$\Pi_D(l) - \Pi_{ND}(l) = p l (q_{ND} - q_D) (R + K) - C_D + C_{ND} \quad (4)$$

$$\Pi_L(d) - \Pi_{NL}(d) = p \{ (R + K) [(q_D - q_{ND}) d + q_{ND}] - K - C_L \} \quad (5)$$

The payoff differential of physicians in equation (4) is an increasing function of l , meaning that the relative performance of defensive strategy D (with respect to that of strategy ND) improves when the population of patients becomes more litigious. Conversely, the payoff differential of patients in equation (5) is a decreasing function of d , meaning that the relative performance of litigious strategy L (with respect to that of strategy NL) worsens when the population of physicians becomes more defensive.

3. Basic results

The system (3) is defined in the unit square S :

$$S = \{ (d, l) \in R^2 : 0 \leq d \leq 1, 0 \leq l \leq 1 \}.$$

All sides of this square are invariant, namely, if the pair (d, l) initially lies on one side, then the whole correspondent trajectory also lies on that side.

Equations (3) and (4) implies that $\dot{d} = 0$ holds if either $d = 0, 1$ or:

$$l = \bar{l} := \frac{C_D - C_{ND}}{p (q_{ND} - q_D) (R + K)} \quad (6)$$

where $\bar{l} > 0$ always, and $\bar{l} < 1$ if:

$$C_D - C_{ND} < p(q_{ND} - q_D)(R + K) \quad (7)$$

Furthermore, it results $\dot{d} > 0$ for $l > \bar{l}$ and $\dot{d} < 0$ for $l < \bar{l}$. Note that the term on the left in inequality (7) represents the cost difference of the defensive strategy (with respect to the not-defensive one), while the term on the right represents the expected benefit difference of the defensive strategy when played against a litigious patient¹.

Analogously, equations (3) and (5) implies that $\dot{l} = 0$ if either $l = 0, 1$ or:

$$d = \bar{d} := \frac{q_{ND}(R + K) - K - C_L}{(q_{ND} - q_D)(R + K)} \quad (8)$$

where $\bar{d} > 0$ holds if:

$$C_L < R q_{ND} - K(1 - q_{ND}) \quad (9)$$

and $\bar{d} < 1$ holds if:

$$C_L > R q_D - K(1 - q_D) \quad (10)$$

It also results $\dot{l} > 0$ for $d < \bar{d}$ and $\dot{l} < 0$ for $d > \bar{d}$. Note that the term on the left of inequalities (9) and (10) represents the cost of the litigious strategy², while the terms on the right represent the patient's expected benefit differences of the litigious strategy (with respect to the not-litigious one) when played, respectively, against a not-defensive and a defensive physician.

According to the above considerations, the four vertices of S :

$$(d, l) = (0, 0), (1, 0), (0, 1), (1, 1)$$

are always stationary states of the dynamic system (3). In these stationary states, the populations of physicians and patients play only one strategy. In $(1, 1)$, all physicians play D and all patients play L ; in $(0, 0)$, all physicians play ND and all patients play NL , and so on.

Another stationary state of the system (3) is the intersection point (\bar{d}, \bar{l}) of the straight lines (6) and (8) if it belongs to the square S . If conditions (7), (9) and (10) are satisfied, it results $0 < \bar{d} < 1$ and $0 < \bar{l} < 1$, therefore (\bar{d}, \bar{l}) belongs to the interior of S and all the strategies D , ND , L and NL coexist. Finally, all the points belonging to the side of S with $l = 0$ (respectively, $l = 1$) are stationary states in the case in which $\bar{l} = 0$ (respectively, $\bar{l} = 1$); analogously, all the points belonging to the side of S with $d = 0$ (respectively, $d = 1$) are stationary states if $\bar{d} = 0$ (respectively, $\bar{d} = 1$).

4. The taxonomy of dynamic regimes

The dynamics that may be observed under the system (3) have been completely classified (see Hofbauer and Sigmund, 1988; Weibull, 1997). We limit our consideration to robust dynamic regimes (that is, we do not consider the regimes occurring only if equality conditions on parameters' values are satisfied). These regimes are illustrated in Figures 1–6. We use full dots, empty dots and squares to represent respectively the attractors, repellers and saddle points. The conditions giving rise to each regime are specified in the following propositions.

Proposition 1. *The stationary state that is globally attractive in the interior of the square S is:*

- $(d, l) = (0, 0)$ if either inequality (7) and the opposite inequality of (9) hold (see Figure 1), or the opposite inequalities of (7) and (9) hold (see Figure 2);
- $(d, l) = (1, 1)$ if inequality (7) and the opposite inequality of (10) hold (see Figure 3);

¹When a physician is matched with a not-litigious patient, the expected benefit difference is equal to zero.

²The cost of the not-litigious strategy is equal to zero; thus the value of C_L can also be interpreted as the cost difference between the litigious strategy and the not-litigious one.

- $(d, l) = (0, 1)$ if inequality (9) and the opposite inequality of (7) hold (see Figure 4 or 5 when it also holds, respectively, inequality (10) or its opposite).

The interpretation of the preceding proposition is simple if we keep in mind the meaning of conditions (7), (9) and (10).

Let us remember that inequality (7) states that the physician's expected benefit difference of the defensive strategy (with respect to the not-defensive one) is higher than its cost difference in a pairwise encounter with a litigious patient³. If inequality (7) holds, then the physician's best responses are *to defend* against litigious patients and *to not defend* against not-litigious patients, while the opposite inequality of (7) implies that the physicians' dominant strategy is *to not defend*. In the former case, the performance of the defensive strategy is better than that of the not-defensive one (and, consequently, $\dot{d} > 0$ holds) when the share l of litigious patients is high enough (*i.e.* $l > \bar{l}$); vice versa if the share of litigious patients is low enough (*i.e.* $l < \bar{l}$), see Figures 1 and 3. In the latter case, the performance of the not-defensive strategy is always better than that of the defensive one, whatever is the share l of litigious patients; consequently $\dot{d} < 0$ always holds in the interior of the square S , as showed in Figures 2, 4 and 5.

Inequality (9) states that the patient's cost difference of the litigious strategy (with respect to the not-litigious one) is lower than its expected benefit difference, in a pairwise encounter with a not-defensive physician. Similarly, inequality (10) states that the patient's cost difference of the litigious strategy is higher than its expected benefit difference, in a pairwise encounter with a defensive physician.

If inequality (9) holds, then litigating is the patient's best response against a not-defensive physician; if inequality (10) holds, then not litigating is the patient's best response against a defensive physician. If both (9) and (10) are satisfied, then the performance of the litigious strategy is better than that of the not-litigious one (and, consequently, $\dot{l} > 0$) when the share d of defensive physicians is low enough (*i.e.* $d < \bar{d}$); vice versa if the share of defensive physicians is high enough (*i.e.* $d > \bar{d}$), see Figure 4.

Note that if the opposite inequality of (9) holds, then patients' dominant strategy is *to not litigate* ($\dot{l} < 0$ always holds, see Figures 1 and 2) while if the opposite inequality of (10) holds, then the patients' dominant strategy is *to litigate* ($\dot{l} > 0$ always holds, see Figures 3 and 5).

Proposition 2. *If inequalities (7), (9) and (10) hold, then there exists a (Lyapunov) stable stationary state $(d, l) = (\bar{d}, \bar{l})$ with $0 < \bar{d} < 1$ and $0 < \bar{l} < 1$, and all the trajectories in the interior of S are closed curves surrounding it (see Figure 6).*

The conditions of Proposition 2 imply that there are no dominant strategies. Figure 6 shows that, when the interior stationary state (\bar{d}, \bar{l}) exists, the values d and l oscillate clockwise around (\bar{d}, \bar{l}) for any initial distribution of strategies $(d_0, l_0) \neq (\bar{d}, \bar{l})$. The initial distribution (d_0, l_0) will be reached again at the end of every cycle. The trajectories around (\bar{d}, \bar{l}) are cyclic because of the signs of the payoff differentials (4) and (5) in each of the four subsets of S delimited by the straight lines (6) and (8).

The interpretation of these dynamics is simple if we remember that, according to equation (4), the relative performance of the defensive strategy D (with respect to that of the strategy ND) improves when the population of patients becomes more litigious (*i.e.* the value of l increases). Conversely, according to equation (5), the relative performance of the litigious strategy L (with respect to that of the strategy NL) worsens when the population of physicians becomes more defensive (*i.e.* the value of d increases). These relations are analogous to prey-predator relations in the Lotka-Volterra model, in which physicians can be seen as preys and litigious patients as their predators. Then, defensive physicians can be seen as adapted preys who improved their Darwinian fitness through mutation from playing strategy ND to strategy D . The increase in adapted preys (*i.e.* defensive physicians) decreases predators' fitness (*i.e.* the payoff differential of litigious patients) leading to a decrease in predators (*i.e.* litigious patients).

³Note that the not-defensive strategy is always the best reply against the not-litigious strategy.

Table 1: Monotonic relations between equilibrium shares and their parameters

	\bar{d}	\bar{l}		\bar{d}	\bar{l}
p	—	↓	K	↓	↓
q_{ND}	↑	↓	C_{ND}	—	↓
q_D	↑	↑	C_D	—	↑
R	↑	↓	C_L	↓	—

Legenda: ↑ Increasing, ↓ Decreasing, — Independent

5. Nash equilibria

A well-known result in evolutionary game theory (see Weibull, 1997, pp. 163-171) is the following. The vertices $(0, 0)$, $(0, 1)$, $(1, 1)$, when attractive, and the interior stationary state (\bar{d}, \bar{l}) , when existing, are Nash equilibria. By Propositions 1 and 2, the one-shot game represented by the payoff matrices (1) and (2) always admits a unique Nash equilibrium. As usual, we can interpret Nash equilibria as *social conventions* in the sense of Lewis (1969); that is, as a *customary* and *expected* state of things in which no single individual has an incentive to modify her choices if the others do not modify theirs.

The Nash-equilibrium property of the interior state (\bar{d}, \bar{l}) does not depend on its stability, as opposed to the pure population stationary states $(0, 0)$, $(0, 1)$, $(1, 1)$, which are Nash equilibria only if locally attractive. Another difference is that (\bar{d}, \bar{l}) is a mixed strategy equilibrium; that is, each available strategy is played by a positive share of the two populations. In the *static* interpretation of the one-shot game, (\bar{d}, \bar{l}) corresponds to the mixed-strategy Nash equilibrium where the physician plays strategies D and ND with probabilities \bar{d} and $1 - \bar{d}$, respectively, and the patient plays strategies L and NL with probabilities \bar{l} and $1 - \bar{l}$, respectively. Another way to interpret (\bar{d}, \bar{l}) is as a proxy for the average values of shares d and l over the periodic time-evolution paths observed along the closed trajectories in Figure 6. In this sense, the interior equilibrium can estimate the behaviour of individuals in random observations over long time periods (see Weibull, 1997).

The closed-form of the trajectories around (\bar{d}, \bar{l}) in Figure 6 does not hold in general but depends on the *standard* replicator equations (3) that we have used. Alternatively, we could use the *adjusted replicator dynamics* of Maynard Smith (1982) (see also Weibull, 1997, p. 172) under which the stationary state (\bar{d}, \bar{l}) may become globally attractive or repulsive in the interior of S . If repulsive, every trajectory starting from an initial state $(d_0, l_0) \neq (\bar{d}, \bar{l})$ will oscillate repeatedly counter-clockwise around the point (\bar{d}, \bar{l}) having the boundary of S as ω -limit set. Thus, under the adjusted replicator dynamics, the point (\bar{d}, \bar{l}) still keeps its importance as either the long-term equilibrium (if attractive) or as a rough proxy for the averages values of d and l over time (if repulsive).

6. Comparative Statics

The influence of parameter variations on the interior stationary state (\bar{d}, \bar{l}) depends on the signs of the partial derivatives of functions (6) and (8), representing the interior equilibrium shares of defensive physicians and litigious patients. The results are summarized in Table 1.

Surprisingly, the equilibrium share of defensive physicians \bar{d} does not depend on the costs of their strategies C_{ND} and C_D nor on clinical risk p , which yet affect patients' equilibrium share. Conversely, the equilibrium share of litigious patients \bar{l} does not depend on the cost of their strategy C_L , which yet affects physicians' equilibrium share. These paradoxical results can be explained by the predator-prey relation between patients and physicians. Accordingly, an evolutionary advantage for a species can be completely offset by a consequent mutation of its competitors. For example, a decrease in patients' legal costs C_L would, *ceteris paribus*, push the share of litigious patients above the equilibrium level; as a reaction, the share of defensive physicians permanently increases, bringing back the share of litigious patients to its previous equilibrium.

The counter-intuitive results can also be explained by means of risk theory. The differential cost of defensive strategy $C_D - C_{ND}$ can be seen as the price for increasing by $q_{ND} - q_D$ the

physician's probability of winning an eventual malpractice lawsuit. Such price is fair when it equals the physician's expected gain from defensive medicine:

$$C_D - C_{ND} = p l (R + K) (q_{ND} - q_D) \quad (11)$$

The preceding equation is equivalent to (6) and, according to equation (4), it implies $\Pi_D(l) = \Pi_{ND}(l)$. The level of defensive medicine is therefore in equilibrium, with a constant share of defensive physicians \bar{d} . Indeed, physicians have no incentives to change their strategies because they all have the same payoff. Any changes in clinical risk p or in physicians' costs C_{ND} and C_D would, *ceteris paribus*, alter this equilibrium and create profit opportunities. Patients are the only ones who can seize these opportunities by switching their strategy, because l is the only endogenous variable in equation (11) that can restore equilibrium. The share of defensive physicians \bar{d} remains therefore stable despite these changes. Similar reasoning applied to equation (8) can show that a change in patients' legal costs C_L affects the share of defensive physicians \bar{d} rather than that of litigious patients \bar{l} .

7. Pareto-ranking of stationary states

The population average payoffs $\bar{\Pi}_{PH}(d, l)$ and $\bar{\Pi}_{PA}(d, l)$, evaluated at the stationary states $(0, 0)$, $(1, 1)$ and (\bar{d}, \bar{l}) are respectively given by:

$$\bar{\Pi}_{PH}(0, 0) = \Pi_{ND}(0) = \pi_{ND}^{NL} = -C_{ND} \quad (12)$$

$$\bar{\Pi}_{PA}(0, 0) = \Pi_{NL}(0) = \pi_{NL}^{ND} = -R p \quad (13)$$

$$\bar{\Pi}_{PH}(1, 1) = \Pi_D(1) = \pi_D^L = -C_D + p [K(1 - q_D) - R q_D] \quad (14)$$

$$\bar{\Pi}_{PA}(1, 1) = \Pi_L(1) = \pi_L^D = -H - p [C_L + (R + K)(1 - q_D)] \quad (15)$$

$$\bar{\Pi}_{PH}(\bar{d}, \bar{l}) = \Pi_D(\bar{l}) = \Pi_{ND}(\bar{l}) = \bar{l} p [K(1 - q_{ND}) - R q_{ND}] - C_{ND} \quad (16)$$

$$\bar{\Pi}_{PA}(\bar{d}, \bar{l}) = \Pi_L(\bar{d}) = \Pi_{NL}(\bar{d}) = -H \bar{d} - R p \quad (17)$$

By comparing the above payoffs, the following proposition is straightforward.

Proposition 3. *The stationary state $(0, 0)$, when it is not attractive, Pareto-dominates:*

- *the interior stationary state (\bar{d}, \bar{l}) , always when existing;*
- *the stationary state $(1, 1)$, when attractive and for high enough ratios H/p .*

The first part of the previous proposition holds for $\bar{\Pi}_{PH}(0, 0) > \bar{\Pi}_{PH}(\bar{d}, \bar{l})$, which is easily verified by comparing equations (13) and (17), and for $\bar{\Pi}_{PA}(0, 0) > \bar{\Pi}_{PA}(\bar{d}, \bar{l})$, which can be verified by comparing equations (12) and (16) and by noting that the first addend in (12) must be negative when the state (\bar{d}, \bar{l}) exists, according to condition (9) in Proposition 2.

The second part of Proposition 3 holds for $\bar{\Pi}_{PH}(0, 0) > \bar{\Pi}_{PH}(1, 1)$ and for $\bar{\Pi}_{PA}(0, 0) > \bar{\Pi}_{PA}(1, 1)$. By comparing equations (12) and (14), the former inequality holds if:

$$C_D - C_{ND} > p [K(1 - q_D) - R q_D] \quad (18)$$

while, by comparing equations (13) and (8), the latter inequality holds if:

$$C_L > -\frac{H}{p} + R q_D - K (1 - q_D) \quad (19)$$

By Proposition 1, a necessary condition for the stationary state $(1, 1)$ to be attractive is the opposite inequality of (10), which implies by simple algebra the inequality (18) and, for high enough ratios H/p , also the inequality (19).

According to the previous proposition, perfect cooperation with neither defensive physicians nor litigious patients is always socially preferable to any mixed-strategy equilibrium with some players for each existing strategy. Perfect cooperation can also be the social first-best for a sufficiently high ratio H/p , that is when either patients' harm from defensive medicine is high enough or the probability of clinical failure is low enough. Notably, the ratio H/p also represents the optimal fine for harms caused by defensive physicians, if p represents their probability of being caught and there are no fine enforcement costs, according to Polinsky and Shavell (1992).

Proposition 3 depends on the assumption that defensive medicine produces a quantifiable harm $H > 0$ to patients. This hypothesis is consistent with the higher costs for superfluous clinical treatments, imposed to patients by physicians and widely reported in literature (for a review see Kessler, 2011). However, if defensive medicine produced a direct benefit to patients (*e.g.* to the hypochondriacs), any change of state would benefit a population of players at the expense of the other. No Pareto-ranking of stationary states would therefore be possible, but the whole population dynamics would be totally unchanged.

8. Conclusions

In the present work, we describe the population dynamics of physicians performing defensive medicine and of patients pursuing medical malpractice litigation, by means of an evolutionary game with exogenous legal, clinical and economic variables. We find that shares of litigious patients and of defensive physicians can follow predator-prey dynamics, with cyclical trends of defensive medicine and malpractice litigation. Variations in clinical risk or in legal and clinical costs can have paradoxical consequences because of temporary divergent effects on physicians and patients. We find that reducing clinical risk may not affect the level of defensive medicine in the long run, but it can increase litigation by patients against doctors. Similarly, increased legal costs may not affect litigation in the long run, but it can increase defensive medicine. These results are proved in a dynamic setting for the first time and they may suggest new theoretical explanations to the heterogeneous results in empirical studies on these phenomena.

We find closed-form solutions that illustrate the impact of legal, clinical and economic variables on physician-patient relations. We demonstrate that any mixed-strategy equilibrium is always sub-optimal with respect to perfect cooperation with neither defensive physicians nor litigious patients. Perfect cooperation can also be the social first-best when either the harm for patients from defensive medicine is high enough, or the probability of clinical failure is low enough.

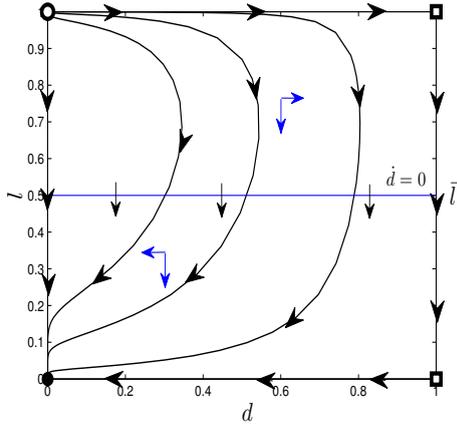
Our system is manageable and can be extended or adapted to the different concepts of defensive medicine in literature. It has the same dynamic properties under the alternative assumptions that defensive medicine produces either a direct harm or benefit to patients. The model can be easily modified to describe also the physicians' provision of superfluous medical care for reasons other than defensive medicine (see for example Currie and MacLeod, 2008). A limitation is that our system excludes ethical and psychological drivers of agents' behaviours, which can be relevant (see for example Vincent, Phillips and Young, 1994). Our findings seem consistent with empirical research on defensive medicine and malpractice litigation, but this needs to be confirmed in future research. Further analyses can include the role of insurers, the impact of insurance covers for physicians and patients, and the possibility for policy makers to achieve the social optimum.

Our analysis suggests that, in the long run, increasing safety in clinical practice can result in persistent levels of defensive medicine and permanent increases in malpractice litigation. Policy makers should pay attention to the overall underlying dynamics of these phenomena and be cautious when interpreting their short-term trends, which may be irregular and misleading. The legal, clinical and economic drivers highlighted in the paper can be properly managed to make the healthcare system more efficient and to lower the social costs of superfluous clinical treatments and undesirable litigation.

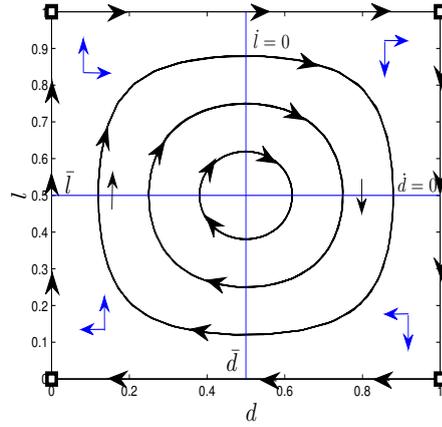
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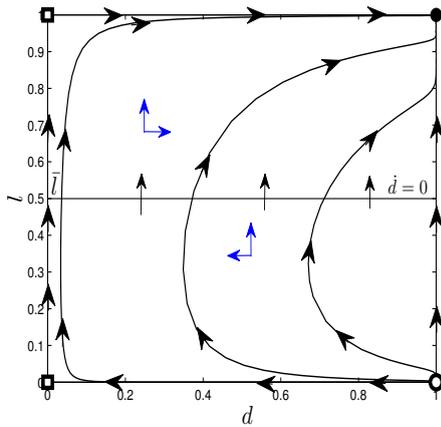
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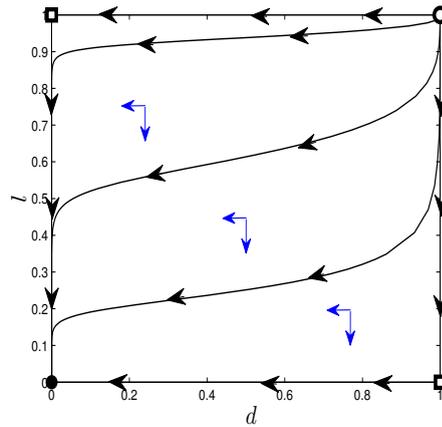
1 Physicians' best responses:
defend against the litigious and the inverse.
Patients' dominant strategy: not litigate.



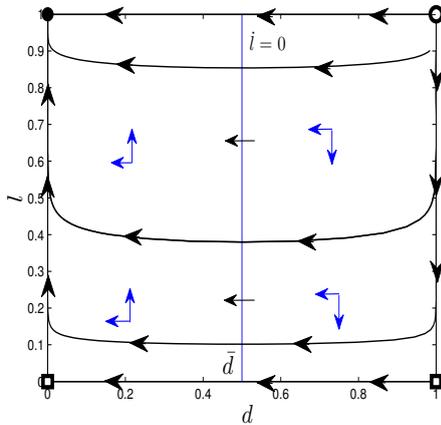
2 Physicians' dominant strategy: not defend.
Patients' dominant strategy: not litigate.



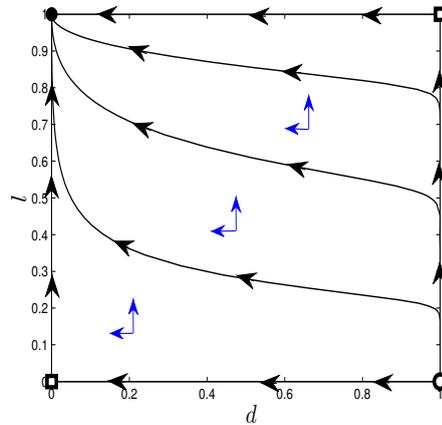
3 Physicians' best responses:
defend against the litigious and the inverse.
Patients' dominant strategy: litigate.



4 Physicians' best responses:
defend against the litigious and the inverse.
Patients' best responses:
not litigate against the defensive, and the inverse.



5 Physicians' dominant strategy: not defend.
Patients' dominant strategy: litigate.



6 Physicians' dominant strategy: not defend.
Patients' best responses:
not litigate against the defensive, and the inverse.

Figures. Dynamic regimes obtained with different parameter sets.

Legenda: d share of defensive physicians, l share of litigious patients, \bullet attractors, \circ repellers, \square saddle points