The Economics of Pharmaceutical Interventions: Vaccination and Treatment

Flavio Toxvaerd
University of Cambridge

Course at Fundação Getulio Vargas
(but sadly not physically in Brazil...)

October 18, 2021

Background

- Currently facing serious global crisis, with COVID-19 fast spreading across the world
- Crisis threatens our health and livelihoods
- With many infectious diseases, possible to manage through pharmaceutical interventions
  - Antivirals increase the rate of recovery
  - Vaccines increases individual and population immunity
- Until recently, these tools not available for COVID-19

Background

- Non-pharmaceutical interventions (NPIs) that induce social distancing include
  - Quarantines, self-isolation
  - Closure of schools, work places, entertainment venues
  - Restrictions on international travel etc.
- These interventions have in common that they influence contact rates in population
- Reduced contact influences progression of epidemic
- Many NPIs very costly, socially and economically
- Treatment and vaccines are low-cost way of allowing reductions in NPIs
- What are optimal treatment and vaccination rollout policies?
- How does social distancing react to unanticipated announcement of pharmaceutical innovation?
- How do such interventions influence behaviour?

Background

- Vaccine rollout in Brazil

Literature

- Hethcote and Waltman (1973),...
  - Traditional non-economic analysis
- Francis (1997)
  - Equilibrium vaccine decisions socially optimal
- Chen and Toxvaerd (2014)
  - Summarise economic approach and literature
- Toxvaerd and Rowthorn (2021)
  - Behaviour fixed, vaccine decisions endogenous
- Makris and Toxvaerd (2021)
  - Vaccine decisions fixed, behaviour endogenous

Traditional approach

- Need to understand SIR dynamics
- Need to define concept of herd immunity
- Traditional public health/epi approach inconsistent with cost-benefit analysis
- Will contrast economic approach to this

What do vaccines do?

- Reduce probability that healthy become infected
- Reduce probability that infected become ill
- Reduce probability that infected transfer infection to others

Prevention of infection:	19.2%
Prevention of transmission:	84.7%
Prevention of serious illness (15-34):	74.0%
Prevention of serious illness (35-70):	49.3%
Prevention of fatality when seriously ill:	92.9%

What do vaccines do?

- Vaccines have external effects
- In general, social and private values differ
- Thus role for public intervention
- Nature of externalities depends on context
- Do people change behaviour?
- If not, can analyse vaccination decision in isolation
- If it does, need to analyse interaction between vaccines and behaviour
- Similar issues hold for treatments

What do treatments do?

- Increase speed of recovery
- Reduce probability that infected become ill
- New antiviral from Merck reduces deaths and hospitalisations by 50%

Mechanics of vaccines and immunity

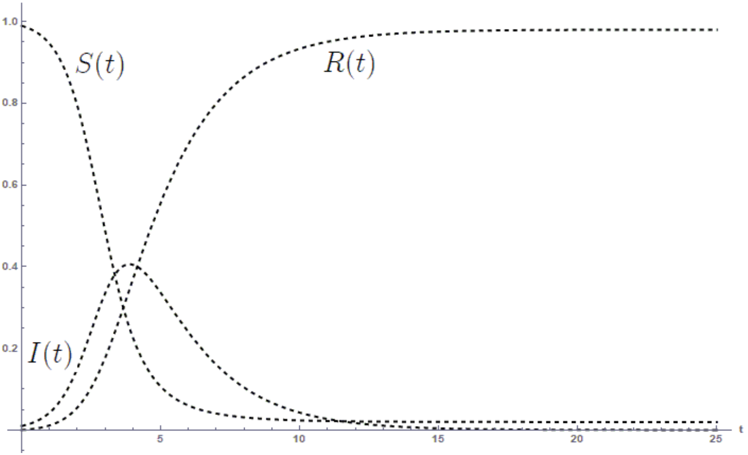
- Consider simple SIR model:

$$\begin{aligned}
\dot{S}(t) &= -\beta I(t) S(t) \\
\dot{I}(t) &= I(t)\left[\beta S(t) - \gamma\right] \\
\dot{R}(t) &= \gamma I(t) \\
S(t) &= 1 - I(t) - R(t) \\
S(0) &= S_0 > \gamma/\beta, \quad I(0) = I_0, \quad S_0 + I_0 = 1
\end{aligned}$$

- Note that $S(t)$ always decreases, $R(t)$ always increases
- But $I(t)$ initially increases, peaks at $S(t) = \gamma/\beta$ and then tends to zero
- Known as herd immunity threshold

Mechanics of vaccines and immunity

- Simple SIR dynamics:



Mechanics of vaccines and immunity

- Why does infection suddenly decrease?
- Over time, fewer and fewer susceptible people left
- They are either recovered (immune) or infected
- Remaining indirectly protected by the immune
- How can we create this outcome artificially?
- By reducing $S(t)$ via vaccination of fraction v
- Dynamic equation becomes

$$\dot{I}(t) = I(t)\left[(1-v)\beta S(t) - \gamma\right]$$

Mechanics of vaccines and immunity

- Have $\dot{I}(t) < 0$ when

$$v > 1 - \frac{\gamma}{\beta S(t)}$$

- Assume that $S(0) \approx 1$ so condition becomes

$$v > 1 - \frac{\gamma}{\beta} = 1 - \frac{1}{\mathcal{R}_0}$$

- Here $\mathcal{R}_0 \equiv \beta/\gamma$ is basic rate of reproduction
- The higher $\mathcal{R}_0$ is, the higher required fraction of vaccinated
- Measles: 94%
- COVID-19: 60-70%

Mechanics of vaccines and immunity

- Fundamental problem: targeting herd immunity threshold incompatible with cost-benefit analysis
- For trivial diseases, not worthwhile to vaccinate at all even if possible (athlete's foot?)
- For serious diseases, best to vaccinate everyone
- Herd immunity threshold interesting as descriptive concept
- Not useful per se to guide policy
- Policy should look to balance costs and benefits $\rightarrow$ use economics
- Also interested in equilibrium $\rightarrow$ intervention warranted?

Social optimality of equilibrium

- Francis (1997) found interesting result
- In simple economic-epidemic model, equilibrium vaccine uptake is socially optimal
- Thus no need to encourage or mandate vaccination
- Chen and Toxvaerd (2914): this result not robust
- Optimality results depends on following assumptions:

1. No spontaneous recovery
2. Vaccination confers instant and perfect immunity
3. Individuals ex ante homogeneous
4. Vaccination completely flexible
5. Individuals infinitely lived

- If any of these violated, equilibrium not socially optimal

Social optimality of equilibrium

- Intuition is as follows
- Each individual compares costs and benefits of vaccination
- Cost is constant but benefits proportional to disease prevalence
- This determines infection risk
- With vaccination a zero-one decision, choice is bang-bang
- Vaccination optimal when threshold I^* reached
- Before this happens, no-one wants to vaccinate
- After it happens, all vaccinate so no-one unvaccinated afterwards
- As vaccine is perfect, no externalities on anyone and equilibrium socially optimal

Vaccination and treatment in SIR model

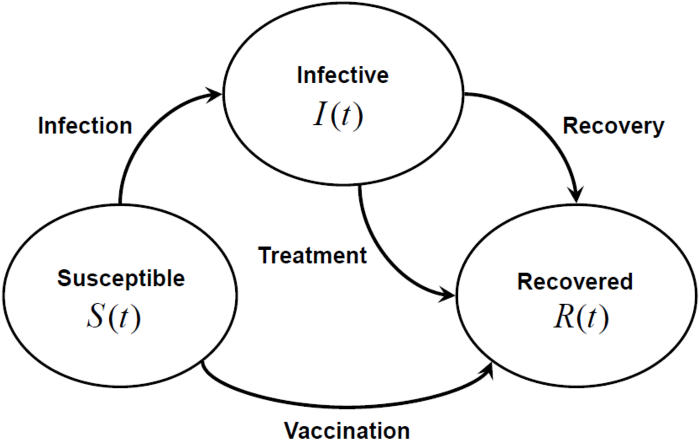


Figure: Perfect vaccines and treatments in SIR model

Vaccination and treatment in SIR model

- Turn model into economic setting
- Health states yield different payoffs with $\pi_{\mathcal{S}} \geq \pi_{\mathcal{R}} \geq \pi_{\mathcal{I}}$
- Future discounted at rate $\rho > 0$
- Treatment $\tau(t) \in [0, 1]$ yields recovery at rate $\tau(t)\alpha_T + \gamma$
- Here $\alpha_T > 0$ is efficiency of treatment
- Treatment costs $c_T > 0$ per instant per individual
- Vaccination $v(t) \in [0, 1]$ yields immunity at rate $\alpha_V v(t)$
- Here $\alpha_V > 0$ is efficiency of vaccine
- Vaccination costs $c_V > 0$ per instant per individual

Socially optimal treatment

- Planner's problem is:

$$\max_{\tau(t)\in[0,1]} \int_0^\infty e^{-\rho t}[S(t)\pi_{\mathcal{S}} + I(t)\left(\pi_{\mathcal{I}} - \tau(t)c_T\right) + R(t)\pi_{\mathcal{R}}]dt$$

- Dynamic constraints are:

$$\begin{aligned}
\dot{S}(t) &= -\beta I(t)S(t) \\
\dot{I}(t) &= I(t)\left[\beta S(t) - \alpha_T\tau(t) - \gamma\right] \\
\dot{R}(t) &= I(t)\left[\alpha_T\tau(t) + \gamma\right] \\
S(t) &= 1 - I(t) - R(t) \\
S(0) &= S_0 > \gamma/\beta, \quad I(0) = I_0 \approx 0, \quad S_0 + I_0 = 1
\end{aligned}$$

Socially optimal treatment

- **Properties of optimal treatment policy:**
- Treatment most valuable early in epidemic but value falls over time
- At most one switch from full treatment to no treatment
- Three possible cases
  - Always treat
  - Never treat
  - First treat and then switch to no treatment
- Treatment yields positive externalities on susceptibles
- But susceptibles decrease over time and so does value of treatment

Socially optimal treatment

- Simulated paths

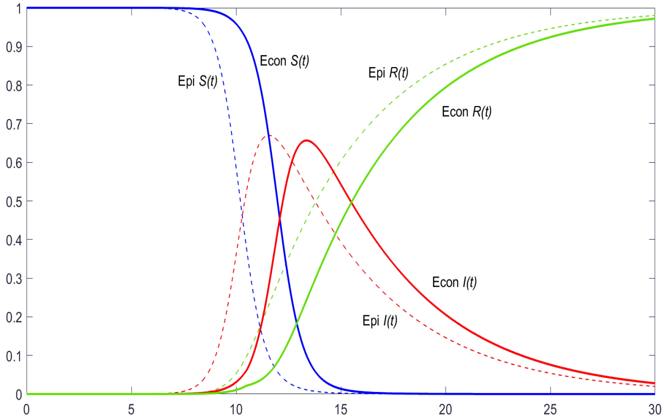


Figure: Controlled versus non-controlled dynamics under treatment

Socially optimal vaccination

- Planner's problem is:

$$\max_{v(t)\in[0,1]} \int_0^\infty e^{-\rho t}[S(t)(\pi_{\mathcal{S}} - v(t)c_V) + I(t)\pi_{\mathcal{I}} + R(t)\pi_{\mathcal{R}}]dt$$

- Dynamic constraints are

$$\begin{aligned}
\dot{S}(t) &= -S(t)\left[\beta I(t) + \alpha_V v(t)\right] \\
\dot{I}(t) &= I(t)\left[\beta S(t) - \gamma\right] \\
\dot{R}(t) &= \gamma I(t) + S(t)\alpha_V v(t) \\
S(t) &= 1 - I(t) - R(t) \\
S(0) &= S_0 > \gamma/\beta, \quad I(0) = I_0 \approx 0, \quad S_0 + I_0 = 1
\end{aligned}$$

Socially optimal vaccination

- **Properties of optimal vaccination policy:**
- Value of vaccination akin to value of lockdowns
- Vaccines moderate transmission from infected to susceptible
- When very few infected, value low
- When very few susceptible, value low
- This creates possibility of non-monotonicity
- Optimal policy can have up to two switches
- Possible sequence: *no vaccination, full vaccination, no vaccination*

Socially optimal vaccination

- Simulated paths

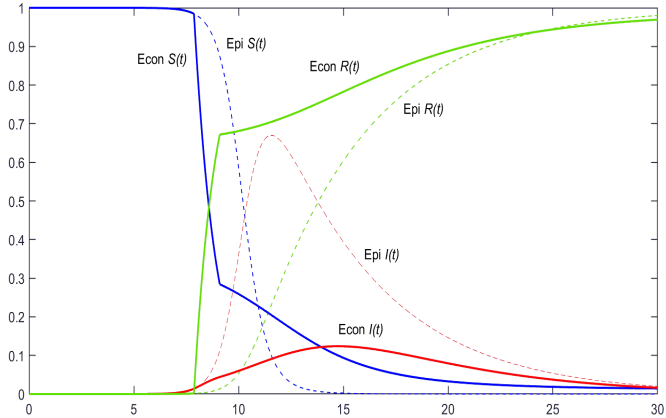


Figure: Controlled versus non-controlled dynamics under vaccination

Equilibrium treatment and vaccination

- **Treatment**
- Qualitatively different from optimal treatment
- Infected individual's choice independent of aggregates
- Treatment only sought if cost low enough
- **Vaccination**
- Qualitatively similar to optimal vaccination
- But because of externalities, less than optimal vaccination

Pre-innovation behaviour and policy

- Let's consider phase before pharmaceutical innovations available
- *Matt Hancock, UK Health Secretary, October 1, 2020:*
- *"Our strategy is to suppress the virus, protecting the economy, education and the NHS, until a vaccine can make us safe"*
- *Donald Trump, US President, November 13, 2020* (after announcing Pfizer vaccine):
- *"[...] this administration will not go, under any circumstances — will not go to a lockdown, but we'll be very vigilant, very careful. [...]. We ask all Americans to remain vigilant, especially as the weather gets colder and it becomes more difficult to go outside and to have outside gatherings"*

Background

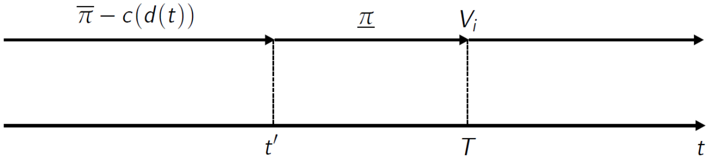
- Will study arrival of treatment and vaccines under:
- Perfect foresight equilibrium → non-cooperative, forward-looking individuals
- Social optimum → utilitarian social planner
- Literature:
  - Auld (2003): behaviour before and after vaccines
  - Models w. stationary arrival of innovations
  - Models w. known date but no post-innovation payoffs

Model

- Continuum population, continuous time, discounted at rate ρ
- At time t individual is in health state $i = \mathcal{S}, \mathcal{I}, \mathcal{R}$
- Payoffs for non-infected $\overline{\pi}$ and for infected $\underline{\pi} < \overline{\pi}$
- Social distancing $d(t) \in [0, 1]$ costs $c(d(t))$, $c' > 0$, $c'' \geq 0$
- At T there is innovation: new treatment or vaccine
- Treatment and vaccine perfect and costless
- Before T, only social distancing
- After T, no need for social distancing so $d^*(t) = 0$ for $t \geq T$
- If in state $i = \mathcal{S}, \mathcal{I}, \mathcal{R}$ at time T, earn V_i $\rightarrow$ expected NPV

Model

- Denote date of infection by t'
- Qualitative difference between $t' < T$ and $t' \geq T$
- Timeline is as follows:



Equilibrium behaviour

- Individual's objective:

$$\int_0^T e^{-\rho t} \left\{ p_{\mathcal{S}}(t)[\overline{\pi} - c(d(t))] + p_{\mathcal{I}}(t)\underline{\pi} + p_{\mathcal{R}}(t)\overline{\pi} \right\} dt$$
$$+ e^{-\rho T}[p_{\mathcal{S}}(T)V_{\mathcal{S}} + p_{\mathcal{I}}(T)V_{\mathcal{I}} + p_{\mathcal{R}}(T)V_{\mathcal{R}}]$$

- Constraints:

$$\begin{aligned} \dot{p}_{\mathcal{S}}(t) &= -(1-d(t))\beta I(t) p_{\mathcal{S}}(t), \quad p_{\mathcal{S}}(0) = 1 \\ \dot{p}_{\mathcal{I}}(t) &= (1-d(t))\beta I(t) p_{\mathcal{S}}(t) - \gamma p_{\mathcal{I}}(t) \\ \dot{p}_{\mathcal{R}}(t) &= \gamma p_{\mathcal{I}}(t) \end{aligned}$$

- State var. $p_i(t) \in [0,1]$ prob. of being in state $i = \mathcal{S}, \mathcal{I}, \mathcal{R}$

Optimal behaviour

- Planner's objective:

$$\int_0^T e^{-\rho t}\left\{S(t)[\overline{\pi} - c(d(t))] + I(t)\underline{\pi} + R(t)\overline{\pi}\right\} dt$$
$$+e^{-\rho T}[S(T)V_{\mathcal{S}} + I(T)V_{\mathcal{I}} + R(T)V_{\mathcal{R}}]$$

- Constraints:

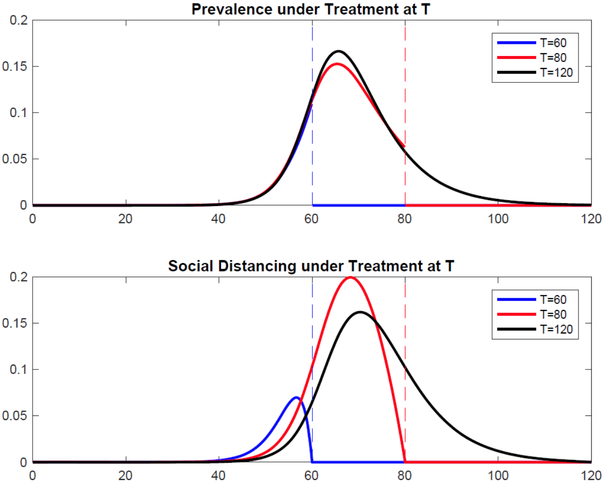
$$\begin{aligned}
\dot{S}(t) &= -\beta(1 - d(t))I(t)S(t) \\
\dot{I}(t) &= I(t)\left[\beta(1 - d(t))S(t) - \gamma\right] \\
\dot{R}(t) &= \gamma I(t) \\
1 &= S(t) + I(t) + R(t) \\
I(0) &\approx 0, I(0) + S(0) = 1, S(0) > \gamma/\beta
\end{aligned}$$

Innovation is treatment

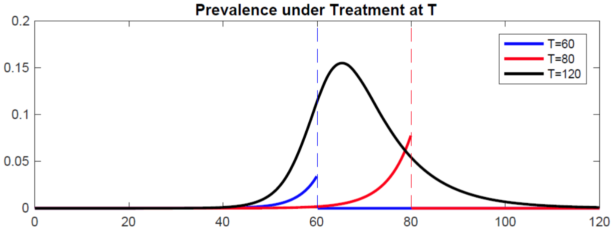
- Suppose treatment costless and yields instantaneous recovery
- When infected, can instantly secure payoff of recovered person $\overline{\pi}$ through treatment
- When susceptible, no need to socially distance as when infected, can treat immediately
- Thus the post-innovation value functions are

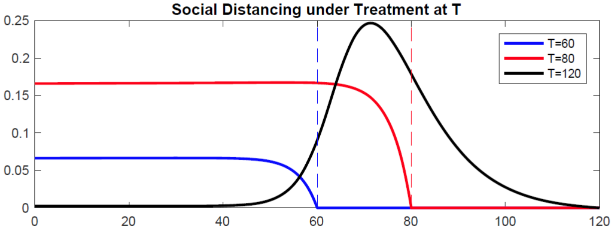
$$V_{\mathcal{S}} = V_{\mathcal{I}} = V_{\mathcal{R}} = \frac{\overline{\pi}}{\rho}$$

Equilibrium treatment



Optimal treatment



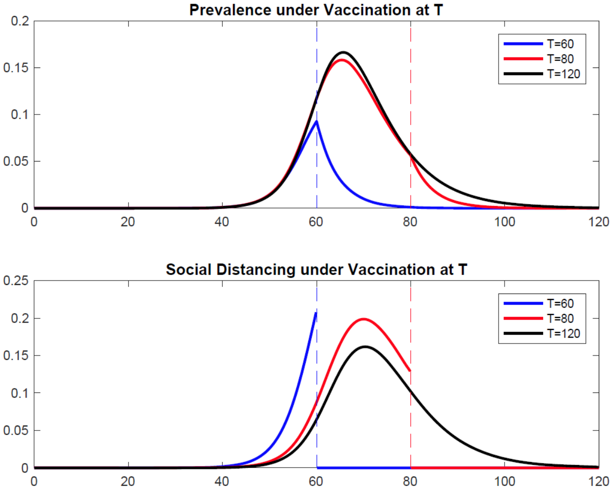


Innovation is vaccine

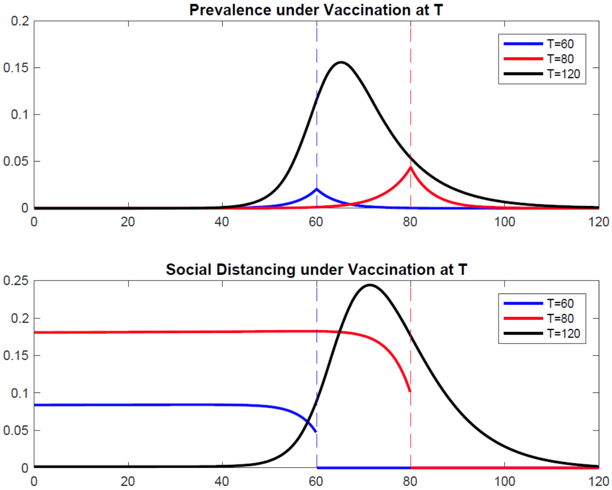
- Suppose vaccine costless and yields instantaneous, complete and permanent immunity
- Any susceptible would immediately vaccinate when possible and would not need to socially distance
- Would therefore earn payoff of recovered person $\overline{\pi}$
- For infected, too late to vaccinate and so earn $\underline{\pi}$ until recovery and $\overline{\pi}$ thereafter
- Thus the post-innovation value functions are

$$\begin{aligned} V_{\mathcal{S}} &= V_{\mathcal{R}} = \frac{\overline{\pi}}{\rho} \\ V_{\mathcal{I}} &= \frac{1}{\rho}\left[\frac{\rho\underline{\pi}}{\rho+\gamma} + \frac{\gamma\overline{\pi}}{\rho+\gamma}\right] \end{aligned}$$

Equilibrium vaccination



Optimal vaccination



Imperfect innovations

- **Imperfect vaccine** that yields incomplete protection:
- After vaccination, still role for social distancing post-innovation
- Lowers $V_{\mathcal{S}}$ so less incentive for social distancing pre-innovation
- **Imperfect treatment** that yields recovery with delay:
- After treatment, still role for social distancing post-innovation
- Lowers both $V_{\mathcal{S}}$ and $V_{\mathcal{I}}$ so ambiguous total effect on social distancing pre-innovation

Going forward

- In practice vaccination in stages b/c of limited stock
- By age, susceptibility etc.
- This introduces new interesting issues and interactions
- Suppose vaccines imperfect; they induce two types of behavioural responses:
- Vaccinated people reduce social distancing, ceteris paribus
- Non-vaccinated also reduce social distancing, ceteris paribus
- Aggregate equilibrium effect in path indeterminate
- Also, what is socially optimal staging?

Private incentives and public objectives

- Have seen that in general, equilibrium outcomes not socially optimal
- Can we do something to improve outcomes?
- Can implement first-best by introducing subsidies and taxes
- Two types:
  - Subsidies/taxes to actions/instruments $\rightarrow$ e.g. payment for vaccination
  - Subsidies/taxes on health states $\rightarrow$ e.g. tax on being infectious
- In practice difficult and/or unethical to implement
- Can consider different second-best instruments
- Can also influence people's decisions directly
  - Restrict social interaction (lockdowns)
  - Introduce vaccine mandates
  - etc.