# Abstract

# Introduction

NPIs during Covid challenged with population compliance.

Mass testing with financial incentives to improve social acceptability (e.g. $5 per test, and ~$5000 for isolation) and mandates to improve reliability. A basic model shows this can be enough to keep R0 <1 for scenarios that previously couldnt be controlled without broad social distancing. The main problem is economic feasibility, but when disease prevalence is kept low the cost of incentivizing isolation is insignificant and samples can be pooled at a high ratio before PCR testing. So it looks like something like this could be done at a cost around 2% of GDP (and lower with more optimizations). 2% of GDP isn’t small, but in a pandemic it could be much better than the alternatives.

Previous studies limited to mathematical model – here we discuss practical implementations along with incentive and enforcement strategies.

While forward looking, basic design only relies on proven technologies. Suggest promising areas for more R&D

During Covid NPIs affecting infectious individuals were disincentivized and measures to protect susceptible people substantially reduced their quality of life. It should not be surprising that many infectious people did not adhere to testing, isolation, and contact tracing recommendations, or that many people decided the cost of social distancing to avoid infection was greater than the danger of getting infected.

Risk-targeted interventions (interventions only impacting people who are infected or much more likely to be infected than the rest of the population) can control epidemics with substantially less burden on the population than alternatives [petrie]. However, risk-targeted interventions depend on information to estimate risk of infection for all members of the population and they require people who are infected to effectively isolate.

Previously NPIs were motivated by either altruism/following social norms, fear of infection, or fear of punishment.

Over-optimistic to expect greater than 80% cooperation based on altruism.

Fear of infection only works for the susceptible population (which is way larger than the infectious population), and many protective measures like social distancing significantly reduce quality of life.

Fear of punishment depends on the government being capable and willing to enforce disease control measures. In democratic countries this usually depends on a majority of the population supporting strict disease control measures. Even in less democratic countries like China there seems to be a limit to what burden from NPIs the population will tolerate before strongly pressuring the government.

Proposal: expand testing capacity to enable legible and minimally invasive mechanism for coordination in pandemic (recent negative test needed to enter public spaces, and infectious are expected to fully isolate). Require these two steps by law, but also provide generous financial incentives (e.g. $5000 for isolation, $5 per test) so that individuals are less likely to find them unfair.

Massive testing and generous financial incentives could be expensive. However the cost of incentives for isolation are proportional to infection rate, and a substantial fraction of the cost of pooled PCR testing is also proportional to infection rate.

Modeling shows high-compliance testing and isolation strategy sufficient for controlling many potential pandemics without relying on any social distancing for non-infected people.

# Challenges with NPIs During Covid-19

During Covid lots of NPI fatigue. closures, social distancing tolerated briefly in time of crisis, but dificult to enforce across whole population for long periods. Social distancing substantially reduced quality of life []. Sometimes wrong NPIs used: e.g. hand washing instead of masks and clean air. Targetted NPIs (NPIs that only impact infected people and their contacts) were not as effective as would be ideal, with 50% isolation compliance at time, 40% contact tracing compliance.

In practice targeted NPIs have had difficulty with reliability

- multiple points of failure (gathering information, making good decisions with information, convincing people to modify behaviour in time to prevent transmissions)

- e.g. 50% compliance with isolation, 30% compliance with isolation, 40% download app, 50% upload positive result, 30% testing rate (which could both be due to barely noticable symptoms, or lack of interest in testing after noticing symptoms), 40% sharing close contacts (on top of inability to reach unknown contacts without using contact tracing app or check-in system)

- if the steps must occur sequentially and the success rate at each step is not high enough then the overall success rate is quite low (e.g. with 5 sequential steps that are each 50% effective, the overall effectiveness is 0.5^5 = 3.1%). Due to magnitude of problem, low success rate actions could still be overwhelmingly worthwhile by partially displacing more costly alternatives [], but they are not enough to solve entire problem.

One reason for low success rate observed during covid is several steps in the targeted NPIs used depended on selfless behaviour from individuals and sufficient attention from under-resourced public health. E.g. contact tracing where a limited number of PH employees convinced people to quarantine after exposure - potentially losing income and leisure during this time for no personal benefit. Surprising targeted NPIs worked as well as they did [] given how actively disincentivized they were. testament to fair amount of pro-social behaviour in time of crisis and hard work by public health (contact tracing etc.). However, in many places targeted NPIs were insufficient alone to bring R0 < 1.

Without strong enough targeted NPIs, Infection rate rose to level where it had to be mediated by either infection-acquired immunity or substantially reduced socialization. This approach of reduced social contacts could be highly effective when supported by the population, but is extremely expensive (banning gatherings for everyone). In addition, broad NPIs were frequently only sufficiently supported when disease rate was relatively quite high (10e-3). This is the main mechanism for disease control that we would predict in a game-theory setting if actors were uncoordinated and self-serving. Maintaining an infection rate at a level where people are personally concerned for their health has several disadvantages: more infections, lower quality of life from fear and costly infection control measures, targeted interventions with cost proportional to infection rate become much more expensive (and less effective due to limited resources).

Prior to Covid, pandemic strategy assumed little willingness or ability to perform NPIs at scale. During Covid, initially substantial public support for social distancing and other disease control strategies. However, limited by lack of capacity (tests, masks). Why researchers focused on scalable digital contact tracing, strategies with limited resources.

# Strategies for Improving NPIs

Build necessary capacity in advance. With benefit of time for R&D in efficient strategies and cost optimizations. Human interface is the hard part- needs to be simple, sensible seeming, and robust to various motivations. Use financial incentives to counteract burden of targeted NPIs on population. Then decision about application of interventions is mainly a budget issue. Here there is more room for sophistication with modern logistics, automation, scalable workforce, and risk targeting

Aim here is to strengthen low cost interventions so that neither many infections or substantial social distancing occur (Like the Ebola response but for viruses with airborne and potentially pre-symptomatic transmission). Would be much more dependable if we can do so without relying on altruistic actions from individuals or heroic efforts from public health. Essentially, can we design a simple mechanism for coordinating (sufficiently) low-cost disease control within a self-serving population?

Improving robustness- simplicity, mandatory, incentivized. Core response only rely on things that can be enforced. Additional things extra. Digital contact tracing potential to help, but many countries not ready to mandate. Incentives essential for fairness, sustainability of strategy, and to further increase effectiveness. Principal aimed for here is for all targetted interventions to be incentivized at a level where majority happy. Eg testing, isolation. Effectiveness of isolation of infectious is essential, because this is the actual intervention being applied- everything else just info gathering. This effectiveness is upper limit of potential for targeted NPIs. Can be quite high like in Aus travelers. In practice it was not strongly enforced in many countries. Perhaps because of worry that making iso more unpleasant would further reduce voluntary testing and contact tracing. Enforcement hopefully enough to increase effectiveness, incentives enough to prevent sabotage. Hope for willingness to follow plan. Alternative incentive schemes could be used to motivate (even self-serving) people to go above and beyond. More sophisticated options possible like phylo, which incentivizes outcome. Motivate earlier testing, mask wearing, contact tracing

Will focus on strategies with as few steps as possible and where (in time of pandemic) it is both politically feasible and practically possible to mandate each step. Restricts what is possible though- seems like public support for mandating contact tracing apps is limited. Infeasible to mandate sharing recent contacts. Worthwhile where possible though - several countries demonstrated that mandating isolation for positive patients is possible and significantly increases effectiveness [AUS, China, Vietnam]. Mandating testing has been accepted in several contexts [].

Need 95% success of most steps. This is totally possible - e.g. 97% drivers in US have an active drivers license

Follow mandate and incentivize approach

Mandate to get compliance above 95%

Incentivize so that at least 80% are happy with the transaction to ensure longevity of approach (among other reasons). Ideally nobody strongly against. Easier if just a nuisance, not something people feel very strongly about (eg vaccines, undue invasion of privacy)

E.g. introduce drivers license somewhere they dont exist - there would be resistance. Modify by adding incentive for passing test- 3000$ or 2 weeks median wage. Much more likely to get support from individuals (neglecting budget issue)

In addition to mandating steps we propose to also incentivize them (both carrot and stick). There are several reasons for doing this:

- even higher compliance

-fairer: targeted interventions impose a significant burden on a small fraction of the population. Success positively impacts whole population so they deserve to be at least partially rewarded for it.

-internalizes previously external costs (which disincentivizes unnecessary use of harmful public health policies like long quarantine or broad social distancing )

-reliable over longer periods (avoid failure modes from Aus and China where lost public support)

e.g. support exceeding wages for isolation

e.g incentive greater than inconvenience of testing

optionally can make this more sophisticated. Not just incentiviszing actions (which we need to take care to avoid Goodhart's Law), but incentivizing outcomes. What we would like is for individuals to not infect others. We can actually detect this using phylogenetics. Proposal: pay people $5k if no evolutionary ancestors detected on phylo tree

# Revisiting Mass Testing

Mass testing proven strategy. Can mandate. Simple. What were problems in other deployments? Fix with incentives, import control, frequency. Simple model and whether it is controlled. Burden on pop subsidized away- main issue is expense

Very simply, the strategy we will explore is to test many people often and isolate positives.

Meets design strategy:

- has few steps: test, isolate positives

- both steps have strong evidence that mandates will be accepted and can be enforced [air travel, Bermuda, Australia]

- possible to incentivize (trivially with payments to fully compensate for time, and potentially with more advanced schemes that we will return to later)

What we are proposing here is not that different from what was implemented in many places (and that is a good thing - the goal is simple, sensible seeming strategy).

Mixed results in real world. explore problems and fix them.

- insufficient frequency [Slovakia, Japan paper]. Interventions must be ongoing unless elimination achieved

- insufficient enforcement of isolation [US college]

- all disease control strategies are sensitive to importation rates. e.g. college community with frequent mixing with general population will see many importations, and this could mask effect of intervention. If possible, much better to reduce links with high prevalence populations (possible to do at country level with border control, or even province level [atlantic canada]).

- Overly unpleasant [china]. No financial incentives, isolated by force, also used centralized location tracking. Quite effective for a while, but even with level of government control eventually lost population support. With less support, less effective, and requires even more interventions, to point where protests and rampant spread. Aim to incentivize compliance, reduce friction, minimize data collection, and be less heavy-handed so that approach is palatable in more countries and could be sustained indefinitely.

Useful to construct a very simplified mathematical model of the strategy to make explicit our assumptions and quantitively analyse points of failure. For simplicity, will only consider this strategy and not combinations of them. In a homogeneous population where fraction $\gamma$ test regularly, fraction $\sigma$ of counterfactual transmissions occur after receiving a positive test (depending on frequency, delay, and relationship between test sensitivity and infectiousness), and transmissions are reduced to fraction $\beta$ after receiving a positive test, the following equation gives the reproductive number.

$R\_t = R\_0 (1 - \gamma \sigma \beta)$

$\gamma$ depends on compliance and accessibility within the population. Ideally can increase by making very easy to get, paying people per test taken, and making it a pre-requisite for daily activities like going into school, work, stores

$\sigma$ depends on the disease and test type, so is not possible to estimate in advance. However can make informed guesses based on data from Covid

Figure \_ shows $\sigma$ depending on testing frequency and delay for Covid-19. (Calculation shown in Supplement \_)

$\beta$ depends on willingness and capability of population to isolate. During covid it varied – around 0.5 in some places, 0.994 in Austrlian travel quarantine []

Figure \_ shows R\_t = 1 cross sections in testing adherence and isolation effectiveness for different values of $\sigma$ for R\_0 = 2.5. R\_0 = 2.5 is chosen here because it is a highly transmissible pathogen that would not be able to be easily controlled if it had substantial presymptomatic transmission. We will show that the basic strategy outlined here is sufficient for control of this pathogen, and discuss extensions that could be used to contain even more transmissible pathogens.

# Cost of Mass Testing

Cost depending on test type, freq, incentives. Can use strategies like \_ to lower cost? Pooled testing

Two scenarios:

1. Pandemic, where there is ability to close borders to high prevalence countries (and ideally keep them open to low prev). Model as 1/100 flow between high prev- leading to below 1/10000 import rate relative to normal flow

2. Business as usual, where border restrictions not possible

First is easier because import rate much lower and because willingness to spend to prevent infections is higher. It is also higher stakes and currently unsolved, so will focus on that in this manuscript.

Dependent on at least some border restrictions, so aim for cost less than that

With a PCR cost of \$40 per test, and \$10 incentive, testing everyone every 2 days with a 1 day test delay costs about 12\% of GDP when importation rate below 1e-4. This cost is dominated by the cost of testing. Only when imporation rate exceeds 1e-4 (in this scenario) that cost of incentivizing and supporting isolation becomes significant.

Nasal-\_ swabs require medical personelle, specialized supplies, and are unpleasant (which in our model directly translates to an increased cost of incentivization). Combined, are quite difficult to scale, and experiments show saliva or gargle test had comparable sensitivity []. Reasonable to expect saliva tests to work for future airborne pandemics as well (at least while infectious) – if the virus is transmitted by breathing, it should be in saliva samples.

12\% GDP worthwhile for deadly pandemic, but quite dificult to mobilize, and harder to make the case for apparently less severe pandemics. Can we reduce this cost?

focus on convenience of intervention so cost of point of indifference drops from \$10 to \$5.

use tests that are more comfortable so price point of indifference lower (saliva rather than nasal)

pooled testing used in many places [] during Covid, but there was limited time to develop optimized systems and the disease prevalence was quite high, so many tests had to be repeated [], increasing the complexity and reducing cost saving from pooled testing

however, in a well-controlled pandemic, the disease prevalence would be so low that the fraction of repeated tests would be insignificant

Testing cost = (1/20 pcrCost + 20 FracPositive \* pcrCost + transportationCost + incentiveCost) \* numTests

along with additional 4 hour delay, and slightly reduced sensitivity []

fracPositive less than importRate\*1/(1-Rt) = R0\*1/(1 - testFraction\*transFraction\*isoFraction)

pooled testing to bring pcr cost down from \$40 to \$5 or less.

with \$10 per test would be 2.4\% GDP - much closer to being an easy choice.

# Potential Further Improvements

Proof of principle of basic case successfully controlling epidemic that would otherwise be devestating at 2% of gdp. Use as foundation- many optimizations likely possible that improve ability to handle more transmissable diseases at lower cost. Iso of household 5x iso cost but potentially less testing needed- prob makes sense to use but didnt want to complicate math model. Phylo incentive to motivate contact tracing (manual, digital, or self) to prompt frequent testing. Targetting in time (if locally eliminated) and space (using wastewater or other surveillance). Cost cutting in PCR. Good masks around people that cant be traced- enforcement? Realtime debugging of failure modes using phylo and other methods. Cost proportional to prevalence in neighbouring countries- game theory to shift?

Proof of principal: by showing that the basic solution would be effective in the easiest important but unsolved scenario: R0 = 2 respiratory pandemic with presymptomatic spread, and an apparent fatality rate low enough that many countries choose not to eliminate it. With current strategies, contact tracing would be able to reduce Rt to 1.5ish until cases got large, and then social distancing and masking would need to be used indefinitely.

extension: within-household contact tracing. Split R0 between household and not household.

$R\_t = R\_{0, H} (1 - \gamma \sigma\_H \beta) + R\_{0, N} (1 - \gamma \sigma\_N \beta)$

Here $\sigma\_H$ is fraction of household contact transmissions to members outside household that occur after the index case has received a positive result. $\sigma\_N$ is the fraction of transmissions to non-household members that would occur after receiving a positive result, and is computed the same way as before. If $\sigma\_N$ is fairly high (>0.7), it $\sigma\_H$ is likely quite close to 1 because there is much more time.

As described, expect to be sufficient for sustained low-cost control of almost completely asymptomatic R\_0 = 2.5 virus, something that existing strategies cannot do. For more challenging scenarios (e.g. R\_0 = 9, or substantial transmission capability on same day of negative test) it still provides a very strong starting point - reduce transmissions by large fraction, failure analysis of transmissions using phylo, norm setting for isolation, very high case detection (albeit delayed) to base contact tracing on. So could conceivably modify slightly and achieve control of dificult pathogens at similar cost (say with addition of immediate isolation of household members, increased testing frequency for contacts, and requirement to mask around strangers)

Can improve even further:

Reduce delay closer to 0 days - can test much less frequently

better automation and cheaper process for PCR

targeting in space/time. with very low importation rate most areas won't have disease most of the time. Any information we can use to decide when/where to do frequent testing?

Detecting and responding to failure modes in mass testing approach. Realtime estimate

Find fraction transmissions in isolation?

# Discussion

Todo: Caveats

Two questions- will it work and is it better than alternatives. Both disease dependent, but for

Further work: de-risk incentive approach with real-world testing. Investigate what investments and/or research could be made in advance to scale testing capacity. Prototype test collection and result sharing. Methods for measuring failure modes (and correcting them)

# Example Implementation

PCR availability early in pandemic

enforcement of regular testing

transportation of samples

Spit in the bucket to enter the store system? Need to provide ID and contact info. Biosafety?

Show id and contact info to camera then spit in bucket on camera

Go to multiple stores = simple to prioritize because all would be positive

only hardware needed is a cellphone (with a camera and internet connection) and a bucket

How to get proof of ‘test’ for places where it isn’t feasible to do this (e.g. buses). Maybe pick up unique QR code from stack and show to camera as well? Then associated with test and ID. Need to

How to solve problem of people not checking phone etc. and learning of positive test result? Is this an actual issue? Next time show QR or ID will get flagged. Would be better if they don’t expose their family/friends before then though