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Herd immunity, COVID-19 and vaccination: some propositions

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Abstract

In the herd immunity path to COVID-19, the scientific world has two broad positions. The Great Barrington declaration called for allowing low-risk population to start activities so that other overriding public health concerns beyond COVID-19 and livelihood aspects of the underprivileged are addressed. As against this, the John Snow memorandum suggested continuing with stricter restrictions to save life and open up only when safe or even emergency use vaccination or therapeutic medication is available. The race for vaccines has been in sync with the memorandum with substantive differences in its distribution within and between countries. A critical look into the maths of herd immunity suggests that the goal should be to reach a threshold level and that too through multiple interventions (including alternative care systems), that a substantive independent intervention like vaccine should show efficacy beyond the aggregate threshold level for relative as also absolute risks and that too beyond trials, that recognizing proximate impact can reduce the need for intervention through direct impact to below threshold level, that the proportion of population one needs to reach out for direct intervention will be lower if it is done through public provisioning, and that identifying and prioritizing for groups with greater exposure (or reproduction number) will reduce the overall weighted threshold level and the proportion of people needing direct intervention. Besides, the advantages of natural immunity for those already infected ought to be recognized. Further, an ethical public health posturing also requires to not having an excessive focus on a single disease, to not limiting interventions for a disease to specific types of care, and to not mandating any specific care.

Keywords: COVID-19, Ethical imperative, Great Barrington declaration, Herd immunity, John Snow memorandum, Public health, Public policy, Threshold level, Vaccination.

JEL Code: C69, D63, H49, I18, I31, I38

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Comments on an earlier version by Jagannath Chatterjee and Sudhir Patnaik as also discussion in the class with two batches of students and research/teaching assistants during January-June 2021 were helpful. The usual disclaimers apply.

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1. Introduction

It has been nearly two years since the onset of the viral outbreak of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in Wuhan, China, in December 2019 [1] [2], with its murky origin [3], and its associated coronavirus disease of 2019 (COVID-19) leading to the ongoing pandemic [4]. The scientific response has been remarkable, but public health concerns beyond COVID-19 and the adverse impact on economy that disproportionately affected the underprivileged led to the Great Barrington declaration (hereafter, the declaration) that called for focused protection of high risk population while allowing low risk population to participate in their day-to-day activities with care and caution [5]. As against this, the John Snow memorandum (hereafter, the memorandum), while agreeing that lockdown restrictions have affected physical and mental health as also harmed the economy, question the rationale of exposing the low-risk population to attain herd immunity through natural infection, and argue for controlling community spread till safe vaccine or therapeutic medication is available [6]. The differences being that the proponents of the declaration indicate that a wait for a safe vaccination or administering one with emergency use authorization will have a greater adverse impact on lives and livelihood and therefore herd immunity through natural infection along with focused protection is better while the proponents of the memorandum are of the view that opening up without controls will take more lives and hence one ought to vaccinate even if it is emergency use authorization to attain herd immunity [7].

2. The Race for Vaccines

Since the end of the first year of the pandemic some vaccines have received country-specific as also World Health Organization (WHO) approval for emergency use authorization [8]. In spite of an appeal to treat vaccines as global common good [9], the distribution of these vaccines within and between countries has been a matter of concern [10].

There has been an appeal by WHO for additional funds, but its suggestion to governments to consider taking loans while economies are contracting can be counterproductive. They pitch their argument on the basis that a safe and effective vaccination will bring about USD 9 trillion by 2025, as per an upside scenario by the International Monetary Fund wherein emerging economies will do relatively better than developed economies [11]. However, one should take this scenario with caution because of the following reasons: there will be variation within emerging economies (China doing much better in July-September quarter of 2020 [12] and thereafter), the low and middle income countries will not have the advantages of emerging economies, and the technological adoption for reducing contact is likely to continue [13], and that this would increase poverty [14] and add to the within and between country inequalities [15].

Besides, if one replaces vaccination with immunity then one opens up other possibilities. There have been studies pointing to advantages of natural immunity after infection, as with other viruses [16] [17] [18] [19]. Moreover, the risks in mortality are relatively lower among working-age and younger cohorts with negligible risks among children, there could be possible adverse effects (known and unknown) of vaccination (as is the case with most drugs), and that while these vaccines may reduce severity and death they do not prevent transmission of infections [20]. Given these, as also ethical concerns with regard to informed consent or even social beneficence [21] [22] [23] [24], what ought to be an approach to vaccination or for that matter any intervention from a public policy perspective. It is in this context, let us look up the maths of herd immunity and derive some propositions.

3. The Maths of Herd Immunity

A public health intervention to obtain herd immunity, ρ, will depend on a base threshold level, θ, derived from the reproduction number, $R_0 > 1$, [25] [26], from which is deducted a parameter, μ, depicting impact of intervention, including network impact [27], such that,

(1) $\rho = \theta - \mu$;

(2) $\theta = 1 - {R_0}^{-1}$, and

(3) $\mu = \sum_i \sum_j \mu_{ij}$

In equation (3), $i = 1, \dots, m$ denote public health interventions, $j = 1, \dots, n$ denote individuals, and μ_{ij} denotes impact of i^{th} intervention on j^{th} individual (for analytical purposes the impact of interventions are considered as mutually exclusive, which implies that interaction effects are considered independently and double counting is avoided). Equations (1)-(3) give us proposition 1.

Proposition 1: For an infectious disease with reproduction number greater than unity, $R_0 > 1$, herd immunity would be achieved if aggregation of impact from all interventions is equal to the threshold level, $\rho = 0 \leftrightarrow \mu = \theta$.

In the context of the ongoing pandemic, a multipronged approach has been linked to the Swiss cheese model [28] [29], which include a package of practices comprising well-ventilated space, nutritious food and hygienic environment, among others. Now, for any single intervention, the population can be divided into three categories $k = d, p, s$, referring to three broad average policy impacts: direct impact, proximate impact on account of network externality, and secluded with no impact, respectively (as an aside, conceptually, this borrows from proximate advantages of illiterates from literates [30] [31] [32], including proximate impact of mother's literacy status on child's health [33], and also from network spillover effect [27]). It is possible that a particular individual could be part of different categories for different interventions. However, for ease of analysis, if we restrict ourselves to a single intervention with individuals categorized into three broad impacts then equation (3) can be written as,

(4) $$\mu_i = \sum_{k_i} \delta_{k_i} \alpha_{k_i} = \delta_{d_i} \alpha_{d_i} + \delta_{p_i} \alpha_{p_i} + \delta_{s_i} \alpha_{s_i}.$$

In equation (4), the population share of k_i^{th}category will be $\delta_{k_i} = n_{k_i}/n \leq 1$ where n_{k_i} is population of k_i^{th}category and n is total population such that $\sum_{k_i} n_{k_i} = n$ and $\sum_{k_i} \delta_{k_i} = 1$. It would be prudent to restrict δ_{p_i} to a range such that $0 \leq \frac{\delta_{p_i}}{\delta_{d_i}} < R_0$ where the lower limit explains that there will be no proximate impact if all those who could have benefitted are now recipients through direct impact while the upper limit suggests that proximate impact cannot be greater than the reproduction number. The efficacy of impact on k_i^{th} category will be $\alpha_{k_i} \in [-1,1]$ where a negative value refers to adverse effect. By implication, $\alpha_{p_i} \leq \alpha_{d_i}$, and $\alpha_{s_i} = 0$. This gives us proposition 2.

Proposition 2: For an infectious disease with reproduction number greater than unity, $R_0 > 1$, an intervention ought to be such that the efficacy of the direct impact should be greater than the base threshold level, $\alpha_{d_i} > \theta$.

Superimposing the implications from propositions 1 and 2 that $\mu = \theta$ and $\alpha_{d_i} > \theta$ and rearranging equation (4) gives us the population share, δ_{d_i}, that should receive intervention through direct impact to reach the base threshold level if there is a single intervention. In other words,

(5) $$\delta_{d_i} = \frac{\theta - \alpha_{p_i}\left(1-\delta_{s_i}\right)}{\alpha_{d_i} - \alpha_{p_i}}.$$

This gives us proposition 3.

Proposition 3: For an infectious disease with reproduction number greater than unity, $R_0 > 1$, the population share that should receive intervention through direct impact will be lower than the base threshold level, $\delta_{d_i} < \theta$,

(a) if an intervention has positive proximate impact through network externality such that $\alpha_{p_i} = \frac{\theta - \delta_{d_i}\alpha_{d_i}}{\left(1-\delta_{s_i}\right)-\delta_{d_i}} > \frac{\theta\left(1-\alpha_{d_i}\right)}{\left(1-\delta_{s_i}\right)-\theta}$ (which is possible if $\theta < \alpha_{d_i} < \frac{\theta}{\left(1-\delta_{s_i}\right)}$) and the proportion not secluded is greater than the base threshold level, $1 - \delta_{s_i} > \theta$, or,

(b) if the proportion of population secluded from intervention is lower than a critical level, $0 < \delta_{s_i} < \frac{\theta\left(\alpha_{d_i}-\alpha_{p_i}\right)+\alpha_{p_i}-\theta}{\alpha_{p_i}}$, and the intervention has positive proximate impact through network externality, $\alpha_{p_i} > 0$.

Now, let us introduce two different policy situations, $l = a, b$. In both these situations, the individual concerned is allowed to take a reasoned decision based on scientific evidence on the intervention, which itself is complex and evolving. In addition to that, in situation a, the policy decision allows public provisioning of the intervention leading to direct impact and does not discriminate on the basis of paying capacity of individuals or other such non-epidemiological or non-medico-legal considerations and there is no seclusion, $\delta_{s_ia} = 0$. As against this, in situation b, the policy decision allows some form of discrimination based on non-epidemiological or non-medico considerations such as open market provisioning with price variation wherein the intervention leading to direct impact will have varying additional costs and this is likely to seclude some proportion of the population, $\delta_{s_i b} > 0$. It follows that,

(6) $$\delta_{d_i b} - \delta_{d_i a} = \frac{\alpha_{p_i}\delta_{s_i b}}{\alpha_{d_i} - \alpha_{p_i}} \geq 0.$$

This gives us proposition 4.

Proposition 4: For an infectious disease with reproduction number greater than unity, $R_0 > 1$, the population share that should receive intervention through direct impact to reach base threshold level will be greater, $\delta_{d_i b} > \delta_{d_i a}$, if intervention is discriminatory and leads to seclusion, $\delta_{s_i b} > 0$.

Keeping the evolving nature of science aside, it is ethically imperative that policy decisions come up with public provisioning of any therapeutic intervention leading to direct impact in line with it being a global public good [9], which will also reduce social costs, $\delta_{d_i a} < \delta_{d_i b}$.

Now, let us introduce a two-group scenario, (say, $g = u, v$), where one of the groups has a greater possibility of reproduction, $R_{0u} > R_{0v}$ such that $R_0 = \sum_g \delta_g R_{0g}; \sum_g \delta_g = 1$, $R_{0u} = \frac{R_0}{\beta}, \beta \in (\delta_u, 1]$, $R_{0v} = \frac{R_0(\beta - \delta_u)}{\beta(1-\delta_u)}$ and $R_{0v} > 1 \leftrightarrow \beta > \frac{\delta_u R_0}{\delta_u + R_0 - 1}$. In such a scenario,

(7) $$\tilde{\theta} = \sum_g \delta_g \theta_g = 1 - \frac{\left[\frac{\beta}{\beta - \delta_u}\{\delta_u(\beta - \delta_u) + (1-\delta_u)^2\}\right]}{R_0} < \theta;\ \theta_g = 0 \ \leftrightarrow R_{0g} \leq 1, g = u, v.$$

To bring in an additional group, let us keep the parameters of one group (say, v, as obtained in equation (7)) as given, and then break down the other to two sub-groups, $u = u_1, u_2$, it follows that $\tilde{\theta}_u < \theta_u$. And, one can extend this to additional groups or sub-groups. This implies that for any intervention that is group-specific (or, meant for the g_i^{th}group, $g_i = 1_i, \ldots, G_i$), because one could prioritize (like medical/paramedical staff, and public utility service providers among others), or, have different interventions for different groups on the basis of epidemiological consideration linked to differences in the reproduction number then it will be socially advantageous, as indicated in proposition 5.

Proposition 5: For an infectious disease with reproduction number being a weighted average across groups, $R_0 = \sum_g \delta_g R_{0g} > 1$, if intervention is prioritized based on group-specific reproduction numbers then the weighted threshold level will be lower than the base threshold level, $\tilde{\theta} < \theta$.

We would like to point out three additional ethical concerns. First, $\alpha_{ij} \nless 0$, efficacy of an intervention, direct or proximate, should not be negative for any individual. This is in line with the dictum of do no harm. Second, $\sum_i \alpha_{ij} \ngtr 1 \forall j$, sum total of efficacy for any individual should not be greater than unity. This is in line with judicious use of the combination of interventions because more than the required use by some could exclude others (particularly so, when resources are limited) and in some cases it may even lead to unintended consequences for those who have used them leading to further use of limited resources on them, which could have been avoided to begin with. Third, $\mu \ngtr \theta$, overall efficacy should not be greater than threshold. This is in line with an effective use of resources from a public health perspective. As resources are limited, the less we use it for a particular disease, the more we will have for other diseases. In fact, a general strengthening of public health preparedness, independent of disease-specific directed interventions, should also be relevant for addressing any specific disease like the current pandemic.

While acknowledging the complexity and evolving nature of the virus, SARS-CoV-2, as also the limitations in our understanding of it, let us further discuss the above-mentioned propositions with examples and counterfactuals.

4. Discussion

First, for SARS-CoV-2, as per certain estimates, $R_0 = 3$, [34] [35]. This implies that a base threshold level of population that needs to be immune to arrest the spread, as per equation (2), will be 67%, or, $\theta = 0.67$.

From proposition 1 and equation (4), it follows that, as a first principle, if there is an intervention or a combination of multipronged interventions that is/are safe and effective then administering the same to 67% of the population is a reasonable goal.

It also follows that those who have been infected and cured have developed natural immunity [16] [18] and could be excluded from interventions that may not have additional advantages or will have relatively less advantage than if those were administered to those who do not have any immunity. This is also in sync with the three additional ethical concerns of doing away with possible harm of an intervention that may not be known, judicious use of resources by not providing more to some as that not only pre-empts other receiving it but also could be harmful to the recipient, and also by releasing resources for other requirement.

Besides, the successes in the initial months (say, in the first year of the pandemic) in containing spread of COVID-19 in Iceland [36], New Zealand [37] [38] [39], South Korea [40] [41], Taiwan [39] [42], and Vietnam [43] [44] [45], as also states of Kerala [46] [47] [48], and Odisha [49] in India, among others, reiterate the importance of effective public health measures that are country-specific or state-specific but also point out the relevance of the coming together of governance and science to make and implement policies that are locally relevant and multipronged.

Second, the basis of an intervention (particularly, when it is claimed to be the substantive one) should be such that the efficacy of direct impact is greater than the threshold level, $\alpha_{d_i} > \theta$, as in proposition 2. This should also be taken into consideration by regulatory authorities before any approval, emergency use or otherwise. Note that five COVID-19 vaccines that received emergency use authorization had their efficacy in terms of relative risk reduction that ranged from 67% to 95% highlighted while their absolute risk reduction that ranged from 0.9% to 1.3% remained hidden in fine print [50] [51].

If there is only one safe and effective intervention without any proximate impact then it has to be administered to $\delta_{d_i} = \frac{\theta}{\alpha_{d_i}}$ proportion of population to reach the base threshold level. Further, if no one has acquired natural immunity and there is no proximate impact then this would imply that for an intervention where relative risk reduction is 67% (or, 0.67) and R_0 gives us a threshold level of 0.67 then each and every one of the population has to be administered with this intervention, $\delta_{d_i} = 1$ (see equation (5) when $\alpha_{p_i} = 0$).

Third, even if one keeps aside the possibility of natural immunity or other effective interventions, a particular intervention can also have proximate impact. For instance, if in a household there are two individuals who if infected can pass on the same to the other but only one of them is exposed to additional risks of being infected because of occupational or other reasons, then by providing immunity through a specific intervention to the individual with greater additional risk of being infected one pre-empts any risk for the other individual also.

One could argue that the base threshold level has already factored in possible network effects of R_0. While acknowledging this, one is building a case for additional proximate impact that may not be obvious in aggregate network effects. Nevertheless, the moot point is that if additional positive impact exists then the proportion of the population to whom the intervention has to be administered to reach the base threshold level will not only be lower than $\frac{\theta}{\alpha_{d_i}}$ but it can also be less than the base threshold level, θ, as indicated in proposition 3.

Now, proposition 3 can be satisfied under two conditions: (a) either the proximate impact is greater than a benchmark, (b) or the proportion of population secluded is lower than another benchmark. The latter is easily verifiable from equation (5). The former, in a situation when $\theta = \alpha_{d_i}$ will only be feasible when efficacy of proximate impact is greater than the efficacy of direct impact. Say, in the household case discussed earlier if there were three members and only one member had additional risks such that providing immunity to this one member will also safeguard the other two members. But, for the purposes of further discussion in the current context, we keep this scenario aside and presume that $\alpha_{p_i} < \alpha_{d_i}$.

Alternatively, if efficacy of direct impact is greater than base threshold level ($\alpha_{d_i} = 0.95$, $\theta = 0.67$) and none of the population is secluded then an efficacy of proximate impact greater than 10% ($\alpha_{p_i} > 0.1$) will imply that the proportion of population that should receive direct impact can be less than the base threshold level ($\delta_{d_i} < \theta$). This, with certain bounds, will also hold as proportion of non-secluded population decreases (but is still greater than the base threshold level, $1 - \delta_{s_i} > \theta$), but at a higher efficacy of proximate impact. In other words, if $\alpha_{d_i} = 0.95$, $\theta = 0.67$, $\delta_{s_i} = 0.2$ then for $\alpha_{p_i} > 0.25$ we will have $\delta_{d_i} < \theta$ such that if $\alpha_{d_i} = 0.30$ then $\delta_{d_i} = 0.66 < \theta$. Note that the population who have been secluded from a safe and effective intervention could be for epidemiological reasons, medico-legal considerations, restricted access, and inability to pay, among others.

Fourth, in the absence of public provisioning there could be seclusion from intervention on account of non-epidemiological and non-medico-legal reasons. Contrasting the situation with and without public provisioning suggests that in the latter scenario the proportion of population that need direct intervention will be higher. If $\alpha_{d_i} = 0.95,\ \alpha_{p_i} = 0.25,\ \delta_{s_i a} = 0,$ $\delta_{s_i b} = 0.2$ then $\delta_{s_i a} = 0.60, \delta_{s_i b} = 0.67$ and $\delta_{s_i b} - \delta_{s_i a} = 0.07$. This shows that under public provisioning the intervention through direct impact will need to be administered to 7% less people to reach base threshold level. This gives further credence to why such interventions ought to be a global common good [9] if they satisfy safety (including from adverse effects) and efficacy (including relative and absolute risk reductions) parameters. Public provisioning or regulation should not be interpreted to mean that coercion of any form (with or without persuasion) should be used to achieve the goal. That would be ethically inappropriate.

Fifth, it is possible that some cohorts or sub-group of population like healthcare workers or vendors among others have a greater exposure and risk, and hence, with a higher reproduction number. A group-specific intervention approach would be prudent. What is more, a weighted average threshold of sub-groups would be lower than the base level threshold. It follows that the proportion of population that should receive intervention through direct impact to reach base threshold level would also be lower.

Now, if $R_0 = 3, R_{0u} = 5,\ \delta_u = 0.2,\ \delta_v = (1 - \delta_u) = 0.8$ then $R_{0v} = 2.5$. It follows that $\theta = 0.67,\ \theta_u = 0.8,\ \theta_u = 0.6,\ \tilde{\theta} = \sum_g \delta_g \theta_g = 0.64 < \theta;\ g = u, v$. This shows that the weighted average threshold of 0.64 is lower than base level threshold of 067. Given $\alpha_{dg} = 0.95, \alpha_{pg} = 0.25,\ \delta_{sg} = 0 \forall g$ we will have $\delta_d = 0.59, \delta_{du} = 0.79, \delta_{dv} = 0.5, \tilde{\delta}_d = 0.56 < \delta_d$. It indicates that if no one is secluded then the proportion of population that should receive intervention through direct impact to attain their respective threshold level will be as follows: 59% without group-wise prioritization, and if a group-specific approach is followed then it will be 79% for high risk group, 50% for low risk group, and 56% for their weighted average.

Besides, any public policy intervention should also exclude those who have developed natural immunity, which may also differ from group-to-group and also across countries or sub-national /regions/cities [52]. It is possible that the reproduction number or efficacy (direct or proximate) of an intervention may differ and this would mean that the proportion requiring direct intervention to reach the threshold level may differ. While acknowledging the same, the moot point that we want to make is that in all possible situations the goal for the intervention need not be the entire population. This also means that allows public provisioning to go hand in hand with informed consent, which is also an ethical imperative.

5. Concluding Remarks

The SARS-CoV-2 virus that has led to the ongoing COVID-19 pandemic has overwhelmed the healthcare systems and disrupted economies worldwide. From a public health perspective there have been two broad perspectives – the Great Barrington declaration and the John Snow memorandum. The former prioritized livelihood as any delays would also adversely affect life while the latter had life as its primary focus, as postponing livelihood concerns is important to save lives. In the first year of the pandemic there have been different public health measures across countries or sub-regions that followed locally relevant and multipronged strategies. Since the beginning of the second year of the pandemic, most countries as also WHO and other multilateral organization, in sync with the memorandum have gone ahead with giving regulatory nod for emergency use authorization of vaccines by articulating that this would help save lives and also in opening up.

The current exercise looked up the math of herd immunity and identified five propositions that have public policy implications for a vaccination strategy. First, any intervention or combination of interventions, which are safe and effective, should keep its goal at the base threshold level, which for a reproduction number of 3 is 0.67 (or, 67% of the population).

Second, if there is only one intervention then the efficacy of that that intervention should be greater than the threshold level, as anything less would mean that we have to reach out to the entire population and if efficacy is unity then the intervention ought to reach out to the proportion of people that is equivalent to the threshold level. In other words, depending on the efficacy the proportion of population that the interventions ought to reach out to will lie between base threshold level (0.67) and unity (that is, 67%-100%).

Third, over and above the network effect captured through the threshold level inherent in the reproduction number, there could be proximate impacts to an intervention, and in some cases the proximate impact could be as good as the direct impact. For instance, if an individual with low risk can only be infected because of proximity to another individual with high risk then if the latter is protected the former will automatically be protected. Acknowledging this will take the goal below the base threshold level. For instance, if base threshold level is 0.67 and the efficacy of direct and proximate impacts are 0.95 and 0.25, respectively, and no one is excluded then the proportion of population that one ought to reach out for direct intervention will be 59%.

Fourth, the absence of public provisioning or public regulation would increase seclusion that does not have an epidemiological basis or medico-legal reason. For instance, if 10% of the population is seclude then from the remaining population the proportion that should be reached out to for direct intervention for attaining base threshold level would be 63%, an increase by 4 percentage points when compared with the third scenario above. This means that leaving these interventions to the open market would not only increase seclusion, but it would also increase prices per unit and require greater uptake among the remaining population to reach the threshold level.

Fifth, if risks for different sub-groups of population are internalized into intervention strategies then it will reduce the proportion of people requiring direct intervention to reach the threshold level. If other things are similar to the third scenario discussed above and if there is one high risk group comprising with 20% of population and having a reproduction number of 5 then the proportion of population that one ought to reach out for direct intervention to attain the weighted threshold level will be 56%, a reduction by 3 percentage points. To this, if one adds those with natural immunity then the requirement to reach the threshold level will further reduce.

A caveat is in order. The reproduction number or efficacy rates and other parameters can fluctuate and need not be the ones that we have used in our examples and counterfactuals. This, however, does not alter the fact that the goal for the intervention need not be the entire population. There is also ample space that allows public provisioning to go hand in hand with informed consent, which is also an ethical imperative. Further, an ethical public health posturing also requires to not having an excessive focus on a single disease, to not limiting interventions for a disease to specific types of care, and to not mandating any specific care.

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