A short study comparing countries on the quality of response to the Covid-19 pandemic

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Abstract

We estimate the overall quality of response to the Covid-19 pandemic in the first 18 months, using a small number of known parameters and a simple formula that is robust to the uncertainties in the data. The population-normalized values of deaths, diagnostic tests, confirmed cases, and doses of vaccines administered were considered. The average infection-fatality-rate provides us a baseline on potential deaths, and along with the test positivity rates in the formula, they add robustness to the estimates of the quality of response. The scores are used to rank countries in two lists representing 84 large countries with a population greater than 10 million, and 85 countries with smaller populations. Additional possible corrections in the rankings of countries to include the per capita purchasing power and the age distribution, are also shown. A few significant inferences are pondered that may help unravel the causes of the poor outcomes. In the last part of the manuscript, it is shown that the presented rankings are robust to the expected uncertainties in the data.

With reported deaths due to the Covid-19 pandemic approaching 5 million it is the worst pandemic (saving HIV/AIDS) since 1920, when a third of the world was infected and more than 20 million people lost their lives to the Spanish flu. When studying large complex problems that do not have a full mathematical description, in the interest of optimal solutions, we have a necessity to quantify the correlation of the outcomes with the inputs using a single number [1]. It becomes further significant in the case of fighting pandemics where a small change in nature of the response by the governments and the people, can produce large changes in the outcomes. The unfortunate deaths due to the multiplicative nature of the communicable disease have an exponentially increasing or decreasing relation with time and the mitigating efforts. This motivates us to derive a relation in section 3 to evaluate the average quality of the response to a pandemic as a single score, using a few measured parameters. First, the observations using this relation and the publicly available data on the Covid-19 pandemic, is reported in section 1. This is followed by a section 2 on a few notable points that may be explored further; the first

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three sections are intended for a wider general readership. The last section 4 establishes the robustness of the rankings presented, in the presence of noisy data that simulates relatively large under-reported deaths or inefficient diagnostic tests, and this may be of interest to readers working on improving such evaluations.

1. Observations and Rankings

The formula in eq. (1) was used to estimate a score S for the quality of response to the Covid-19 pandemic, along with values reported until Aug 31, 2021 [2, 3]. While a delay of up to 4 weeks in reporting the number of the administered vaccination doses are possible, the other parameters were updated daily. The deduction of this formula is presented in section 3. The rankings of countries are based on S with the lower scores representing a better quality of response and a higher ranking. Here T, V, C and D represent population-normalized values of the tests, vaccine doses, confirmed cases, and deaths (per million people).

$$S = \log(1 + FG) \text{ where } F = \frac{a_0 D}{e^{-(\frac{a_0 D}{D_0} + \frac{p}{p_0})}\sqrt{VT}} \text{ and } p = \frac{C}{T} \tag{1}$$

where G is the GDP per capita in PPP terms for the country scored, giving us the units of dollars per vaccine (or dollars per test) for the evaluated scores. For the *actual* rankings, the average per capita GDP of the world (or possibly any other constant) for G, along with a_0=1 were used. This implies that there is no compensation in scores for the varying economic conditions and relative size of the senior population (> 65 years of age) among countries. On the other hand, for a compensated ranking with a hypothetical parity in economic and age factors of the populations, we use a varying G given by the per capita GDP of the country, and an a_0 given by the ratio of the fraction of the senior population globally and the fraction of seniors within the country [4]. Also, note that there is no reasonable way to compensate for the variations in geographies or the population densities of countries that impact the response to the pandemic. Thus, one may argue that the actual ranks are most appropriate for conclusions on the quality of response of the governments and the people, given the differing but known conditions they are subject to. The actual rankings and the compensated rankings have large differences only for some countries in West Asia where the per capita GDP is high but the fraction of senior population is low, and these countries lose significantly in rankings due to this compensation. Similarly, a few countries in Africa with a reasonable fraction of seniors but a low per capita GDP, gain significantly in this compensated ranking.

We use an average infection mortality rate of 0.3% representing the global age distribution to arrive at a D_0 of 3000 deaths per million expected when everyone is infected [5, 6]. Similarly, the suggested maximum value of p (test-positivity-ratio) by the world-Health-Organization (WHO) is 0.1 beyond which tests become increasingly useless in breaking chains of transmission, and we use $p_0 = 0.1$ for the half life of p. A study of the robustness of the ranking to the expected levels of noise in the data, is presented in section 4. Under-recording of deaths and any over-reporting/inefficacy of tests can reduce the reliability of ranking, and reported values may vary up to 100% even in well governed countries due to sharp waves of the pandemic when the medical and administrative systems get overwhelmed. For example, a minimum 25% under-recording of Covid deaths has been determined in the United States [7, 8]. Section 4 establishes that in the presence of up to 100% noise in the data, representing the under-reporting of deaths or inefficiency of tests, the average change in the ranking of the countries is less than 4. The average change in the rank for noise up to 200% in the data is less than 5. These predictions include a confidence of 99%.

2. Notes for consideration

The ranking tables of the small and large countries establish that the pandemic's devastation has touched all parts of the globe regardless of the economic, geographic and demographic variations. The top ranks have mostly been occupied by countries with low population densities and relatively insulated borders. It also shows that the mitigation efforts have not provided the results generally expected twelve months ago, given the no-response baseline and the known infection-mortality-rates determined for the unvaccinated people early-on during the pandemic. The contrast of these rankings with the human development indices (HDI) of countries should be noted as well. One has to wonder if the scientific and political efforts have been sub-optimal in ending the pandemic sooner. More specifically, a well-designed administration of vaccine doses prioritized finely on age, and distributed based on population-density and the applied social distancing measures could have further reduced deaths, though it may have been politically unpopular. This might have as well released some of the evolutionary pressure on the virus to mutate into variants that can hide from our immune system, and further become dominant in the population [9]. Considering that the efficacy of the vaccines and the rates of vaccination were bound to be well below the required levels globally, scientific studies on optimal rates of vaccination based on these evolutionary aspects should have been emphasized. Note that when New York had the last outbreak of small pox in 1947, the entire population of 6.5 million had to be vaccinated within a month to get rid of the pandemic, and the Covid-19 virus has a similar rate of transmission. The expectation that people vaccinated under the Emergency-Use-Authorization would be tracked for quantitative assessments on the duration of immunity, has not been met as well. Easy to administer, more compliant and transmission-arresting nasal vaccines may provide a realistic longer-term option against the virus [10, 11], that may otherwise require multiple intra-muscular vaccine doses for a person every year.

More surprising is the lack of effective anti-virals, repurposed drugs and other protocols for treatments of the symptoms and the disease itself. Questions on how one should establish 'control' in randomized control trials in the times of a raging pandemic have risen, especially in the case of potential treatments where the meta-analyses of repurposed therapeutics show clear benefits [12, 13, 14, 15]. Note that in an ideal control trial, a notable fraction of the infected are supposed to be treated only with a placebo, which could be unethical considering the risks associated in this pandemic [16]. Such questions are many times intertwined with the economic impacts, and has led to inconsistencies both among the medical professionals and within the regulatory authorities, and resulted in ad hoc treatment protocols and advisories [17, 18]. The unknown origin of the virus and the pandemic may also have had a huge effect on the scientific outcomes in finding a mitigation or cure for the disease [19]. Considering that the warming climate and intensive animal farming could be augmenting factors for future outbreaks of viral diseases [20, 21, 22, 23, 24], this lack of understanding of the origin of the pandemic could

Actual Rank	Country	Age & GDP Comp. Rank	Deaths / Million
1	**Bhutan**	1	4
2	**Singapore**	4	9
3	**New Zealand**	2	5
4	**Hong Kong**	6	28
5	**Laos**	5	2
6	**Vanuatu**	3	3
7	**Brunei**	16	25
8	**Iceland**	9	96
9	**Mauritius**	7	24
10	**UAE**	38	204
11	**Grenada**	8	27
12	**Denmark**	11	444
13	**Norway**	15	150
14	**Cyprus**	13	416
15	**Finland**	12	186
16	**Barbados**	10	177
17	**Mongolia**	22	284
18	**Maldives**	26	410
19	**Qatar**	66	214
20	**St. Vincent Grenadines**	18	108
21	**Gabon**	28	73
22	**Togo**	14	22
23	**Austria**	21	1189
24	**Timor-Leste**	20	53
25	**Bahrain**	60	784
26	**Equatorial Guinea**	42	87
27	**Malta**	23	996
28	**Israel**	31	760
29	**Luxembourg**	44	1301
30	**Sierra Leone**	17	15
31	**Congo**	25	32
32	**Belarus**	24	401
33	**Curaçao**	27	879
34	**Ireland**	52	1022
35	**Liberia**	19	28
36	**Latvia**	32	1386
37	**Estonia**	36	975
38	**El Salvador**	29	450
39	**Kuwait**	75	557
40	**Djibouti**	35	156
41	**Aruba**	48	1361
42	**Switzerland**	53	1260
43	**Antigua and Barbuda**	47	445
44	**Fiji**	50	558
45	**Lithuania**	39	1710
46	**Belize**	46	892
47	**Gambia**	37	129
48	**Mauritania**	49	150
49	**Guinea-Bissau**	33	59
50	**Papua New Guinea**	40	21
51	**Guyana**	57	789
52	**Kyrgyzstan**	45	381
53	**Lesotho**	34	186
54	**Serbia**	41	840
55	**CAR**	30	20
56	**Cabo Verde**	55	558
57	**Botswana**	69	939
58	**Georgia**	43	1900
59	**Sao Tome and Principe**	56	165
60	**Panama**	65	1608
61	**Albania**	51	870
62	**Jamaica**	54	520
63	**Lebanon**	58	1187
64	**Trinidad and Tobago**	61	927
65	**Bahamas**	74	958
66	**Oman**	81	774
67	**Eswatini**	76	947
68	**Slovakia**	63	2297
69	**Croatia**	59	2046
70	**Costa Rica**	72	1073
71	**Libya**	77	611
72	**Hungary**	64	3121
73	**Slovenia**	68	2142
74	**Moldova**	67	1592
75	**Bulgaria**	62	2751
76	**Montenegro**	71	2757
77	**North Macedonia**	70	2863
78	**Armenia**	73	1642
79	**Namibia**	82	1305
80	**Suriname**	79	1223
81	**Paraguay**	83	2182
82	**Bosnia and Herzegovina**	78	3014
83	**Honduras**	80	890
84	**Seychelles**	84	1050
85	**French Polynesia**	85	1577

Table 1: List of small countries with a total population less than 10 million. Publicly available values [2, 3, 4] reported until Aug 31, 2021 were used in the evaluation, and the data is submitted along with the paper.

Actual Rank	Country	Age & GDP Comp. Rank	Deaths / Million	Actual Rank	Country	Age & GDP Comp. Rank	Deaths / Million
1	**China**	1	3	43	**Jordan**	62	1010
2	**Australia**	2	39	44	**Uganda**	40	64
3	**S. Korea**	3	45	45	**Ethiopia**	26	40
4	**Taiwan**	5	35	46	**Sweden**	53	1440
5	**Saudi Arabia**	37	241	47	**Kenya**	51	86
6	**Cambodia**	4	113	48	**Spain**	47	1806
7	**Benin**	8	10	49	**USA**	61	1980
8	**Japan**	11	128	50	**Italy**	43	2142
9	**Rwanda**	6	82	51	**Belgium**	54	2179
10	**Uzbekistan**	14	32	52	**Dominican Republic**	60	365
11	**Guinea**	10	25	53	**Czechia**	48	2833
12	**Vietnam**	12	121	54	**Chile**	56	1913
13	**Canada**	22	707	55	**Mozambique**	27	58
14	**Niger**	7	8	56	**Egypt**	65	160
15	**Nigeria**	23	12	57	**Bangladesh**	50	158
16	**Cuba**	13	475	58	**Indonesia**	64	483
17	**Malaysia**	42	516	59	**Myanmar**	49	282
18	**India**	15	315	60	**Somalia**	31	60
19	**Ghana**	24	33	61	**Iraq**	71	506
20	**Pakistan**	17	115	62	**Nepal**	52	362
21	**Angola**	35	36	63	**Romania**	63	1812
22	**Kazakhstan**	44	499	64	**Malawi**	57	111
23	**Turkey**	41	667	65	**Poland**	66	1994
24	**South Sudan**	9	11	66	**Madagascar**	59	34
25	**Venezuela**	32	143	67	**Sudan**	68	63
26	**UK**	28	1943	68	**DRC**	58	11
27	**Morocco**	19	341	69	**Iran**	72	1272
28	**Burkina Faso**	18	8	70	**Guatemala**	73	656
29	**Mali**	20	26	71	**Afghanistan**	70	178
30	**Greece**	21	1319	72	**South Africa**	77	1371
31	**Cameroon**	29	50	73	**Ukraine**	67	1241
32	**Sri Lanka**	25	437	74	**Bolivia**	74	1558
33	**Germany**	39	1103	75	**Haiti**	69	51
34	**Chad**	16	10	76	**Colombia**	75	2427
35	**Azerbaijan**	46	554	77	**Argentina**	76	2452
36	**France**	38	1751	78	**Tunisia**	78	1968
37	**Russia**	36	1266	79	**Syria**	79	112
38	**Thailand**	33	173	80	**Ecuador**	80	1799
39	**Portugal**	30	1747	81	**Peru**	81	5919
40	**Philippines**	45	303	82	**Brazil**	82	2712
41	**Senegal**	34	103	83	**Mexico**	83	1996
42	**Netherlands**	55	1048	84	**Algeria**	84	118

Table 2: List of large countries with a total population greater than 10 million. Publicly available values [2, 3, 4] reported until Aug 31, 2021 were used in the evaluation, and the data is submitted along with the paper.

prove more costly in a future outbreak. There is always the possibility of a novel virus emerging that is as contagious as Covid-19 but with a higher rate of mortality.

The second aspect that is not directly apparent in these evaluations but one that saved many lives, is the timely governance in the face of exponentially increasing cases in an acute wave of the pandemic. Bhutan stands out in its response though it may not be ranked highly in the human development index, and it should be no surprise for the readers familiar with its focus on social indicators such as *Gross National Happiness* (GNH). Singapore with its strict measures of social distancing succeeds in keeping the deaths despite a relatively high population density. Europe and South America are two continents that have been most impacted by the pandemic; with only few countries like Norway, Finland and Denmark being able to keep the pandemic relatively in check. The most populous country of China was expected to do well considering the permanent one-party rule and its unlimited power. The scientific prowess of China and its unique advantages as the reported origin of the pandemic may also have played a role in its excellent response to the pandemic and be ranked at the top. The intensity of the pandemic and the testing rates (a total of 65 confirmed cases and ∼110,000 tests per million) have been among the lowest in the world for more than a year. This has been attributed mostly to the high vaccination rates, but with the poor efficacy of its vaccines observed in Seychelles, parts of South America, and UAE (where even children are administered), the data reported from China presents us with many contradictions. The other large country of India was expected to be consumed by the pandemic more than the smaller or the developed countries. The outcomes in India have been notably better than most parts of the world in its response to the pandemic, and ranked at 18 it is among the top quarter of countries. But, the devastating second wave of Covid-19 presented questions on the role of both the central/federal institutions on the issue of appropriate advisories and tracking of dangerous mutants [25], and the local governments at the states in not preparing for eventualities like the demands of oxygen. Note that cost and time effective solutions for generation of medical grade oxygen were described, available and mandated with appropriate licensing measures, a year before the onset of the second wave in India [26, 27, 28]. Unfortunately, the oxygen generating plants put into operation by the state/local governments after the second wave, may not be essential until a third wave of the pandemic [29, 30]. A more appropriate response of the government and the people going into the second wave could have reduced its total death toll by a quarter, and India may have ranked higher at 14. This challenge of timeliness or the *quality* of response to a raging pandemic has put stringent demands on governments and the people, and a delayed response of a great *degree* is seldom of consequence.

3. Building a formula for the quality of response

If we chose a formulation that minimises the scores for a higher quality of response, the scores assigned have to increase with the deaths reported. The deaths considered are as fractions of the total population, deaths per million for example, to account for the varying populations of the countries. The number of tests, confirmed cases and vaccination doses used in the evaluation are also population-normalized values. The deaths due to the disease alone do not qualify the response to the pandemic, when one has additional objectives such as protecting the livelihoods and the potential deaths due to other concomitant causes. Direct interventions on the diseased such as effective

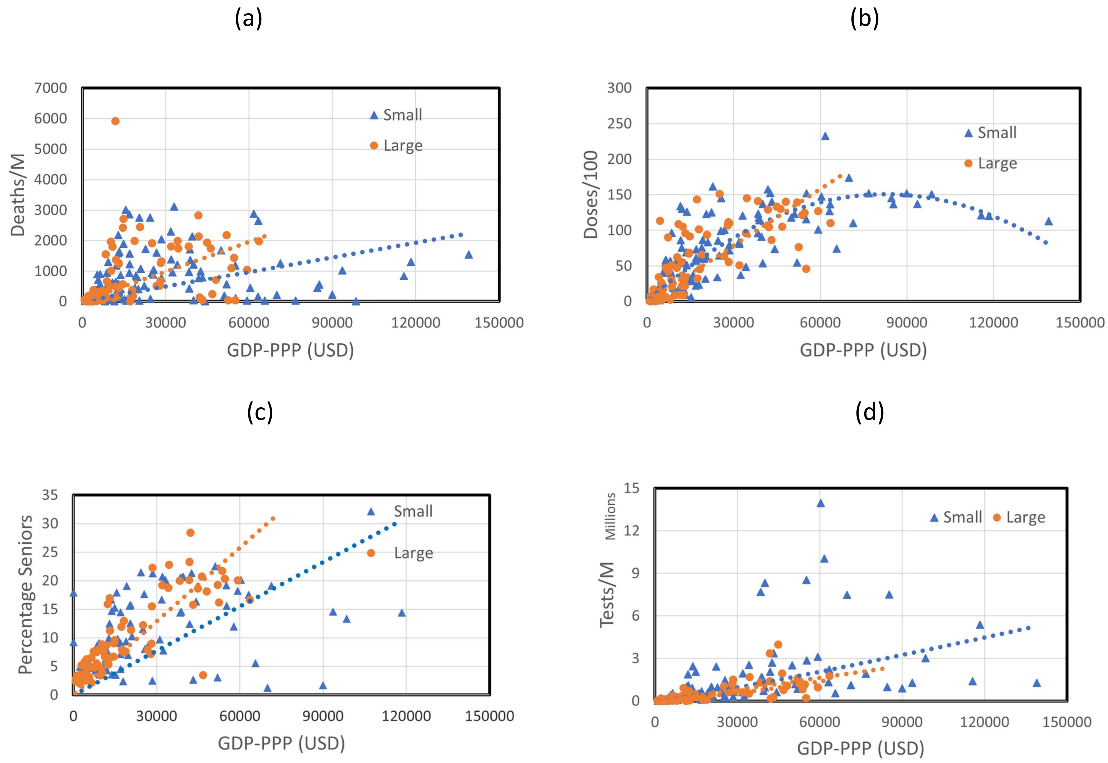

Figure 1: (a) Deaths per million; (b) Vaccine doses per 100 people; (c) Fraction of senior population in percentage; and (d) Tests per million; All plotted with the corresponding per capita GDP values.

treatments of the symptoms, or potential cures for the disease, indeed manifest as lower number of deaths. But the varying onsets and degrees of the pandemic in countries, and the mitigating response of the governments and people have to be considered. For example, vaccination can prevent potential deaths in the future, and diagnostic testing furthers the effective treatments, and also helps in reducing the transmission of the disease if used along with the measures of social distancing. Inclusion of tests and vaccinations in the formula for the quality of response also adds to its robustness when the deaths reported can have variations due to differing medical classifications and administrative efficiencies.

Before we embark on building a formula, let us look at the correlation of the significant parameters with a known causal factor i.e. the correlation of deaths, diagnostic tests and vaccinations with the purchasing power in the population [2, 3, 4]. In this work we use the per capita GDP in purchasing power parity (PPP) terms reflecting the resources available to a person in the population, and not the per capita *nominal* GDP estimated in dollar prices of goods, which is relatively less relevant. Counter-intuitively, the deaths have a strong positive correlation with per capita GDP of the country as shown in Figure 1a for both the small and large countries i.e. higher the per capita GDP, higher the likely number of deaths. Figure 1c unravels this causal relationship; higher the per capita GDP, higher is the life expectancy and the fraction of seniors (> 65 yrs of age) in the population. It should be noted that the Covid-19 has infection-fatality-rates that increase exponentially with the age group (see figures 3 and 4 in [6]). The infection-fatality-rates represent the probability of death for an infected person, and it is different from the case-fatality-rates which considers only the confirmed cases. The former are typically estimated using the sero-prevalence of anti-bodies in the population, and less reliably using excess deaths observed, thus including the unreported infections as well. From a low mortality rate (< 0.01%) for people less than 30 years of age, it increases exponentially to cross 1% for ages above 65 [5, 6]. The case-fatality-rates also set a reliable upper bound on the infection-fatality-rates. Figures 1a and 1c also show that the smaller countries (blue triangles) constitute two distinct groups - one with a higher GDP per capita and a correspondingly aged population, and another group of off-shore financial hubs, tourist destinations and oil-producing countries that have a high per capita GDP but a smaller senior population. Figures 1b and 1d also confirm the expected increase in testing and vaccination rates with the increase in the per capita GDP of a country. The above correlations allow us to ascertain how the positive factors such as vaccine doses (V) and the number of tests (T) in population-normalized numbers, compare to deaths per million (D), given the per capita GDP-PPP (G) of a country. Let the corresponding ratios of the negative factors and the positive factors be given by F below:

$$F = c_0 \frac{\frac{D}{G}}{\sqrt{\frac{V}{G} \cdot \frac{T}{G}}} = c_0 \frac{D}{\sqrt{VT}} \tag{2}$$

where we have used the *geometric* mean given by the square-root of the vaccination and testing rates, to retrieve a value of F that is independent of the GDP and includes only the main parameters of interest here. In contrast to an arithmetic mean (average), the geometric mean of the testing and vaccination effort in breaking the chains of transmission, also has an implicit inference. It implies that the tests or the vaccinations cannot be *completely* replaced by the other, and a lower value in one disproportionately reduces effectiveness of the response. The constant c_0 relates the optimal ratio (scaling) of vaccinations and tests, and estimating it is beyond the scope of this work. Here we set it to 1 without affecting the relative rankings of countries. When the values of F are used to compare responses for two different pandemics, estimating a specific c_0 may become indispensable. While F in equation 2 used only the idea of correlations, and is a reasonable point to begin with, it requires further additions to increase the robustness of the formula. This can be typically done by considering some fundamental conservation property of the problem. Both, vaccinations to add immunity to the population and the tests performed for breaking the chain in the transmissions, have to be reasonably optimal and finite. Vaccinations contribute effectively to reducing deaths if administered before the majority of the people are exposed to the pathogen, and also the possibility of partially effective vaccines have to be included. Similarly, testing helps in breaking the chain only if a small fraction of the tests are positive i.e. sufficient number of tests are performed. The above conditions imposed by the problem can be included in evaluating F as below.

$$F = \frac{D}{e^{-(\frac{D}{D_0} + \frac{p}{p_0})} \sqrt{VT}} \text{ where } p = \frac{C}{T} \tag{3}$$

Thus, there are two exponential factors in F modulating the effectiveness of the vaccinations and tests. The *half-life* of these factors (D_0 and p_0) determines the fully effective regions given by the very small values of D and p, and the ineffective regions given by their large values. D_0 represents the potential deaths when all the million people are infected in the absence of vaccines and the treatments available to the patients remain unaltered. Note that large gains in immunity due to the vaccine accrue when most of the population is yet to be infected with the actual pathogen at least once i.e when the deaths $D \ll D_0$. Also, an ineffective vaccine results in the unfortunate eventuality of $D \sim D_0$ as has been observed in parts of the world, and thus the above formula takes into account such cases. Similarly, the tests (T) are corrected using the known average test positivity ratios p in $exp(-\frac{p}{p_0})$, for their use in the prevention of transmission. A large positivity ratio p i.e. larger fraction of positive results C in the tests T, implies the tests have been largely used in confirming cases with already strong symptoms. This factor can also be interpreted as a correction factor to the deaths D in the numerator, for under-reporting of Covid deaths due to inadequate testing. Other under-recordings of deaths due to varying medical classifications used and the administrative efficiencies, are left uncorrected. But, the lower sensitivity of the rankings due to such uncertainties in the data are shown in the section 4. An ideal scoring formula satisfies the basic notions of the problem and produces well distributed scores representing the changes in the input data i.e. it displays adequate sensitivity in the entire range of the input data. On the other hand, it should not exhibit too much sensitivity where the noise in the data dominates the ranking established by the scores.

For our convenience, we can suppress the exponentially varying values of F without affecting the ordering of the scores or the resulting rankings, by using the log-function.

$$S = \log(1 + FG) \text{ where } F = \frac{a_0 D}{e^{-(\frac{a_0 D}{D_0} + \frac{p}{p_0})}\sqrt{VT}} \tag{4}$$

where G represents the GDP per capita in PPP terms for the population scored, giving us the units of dollars per vaccine for the evaluated scores. For the *actual* rankings of countries, any constant value of G and a_0, like the average per capita values of the world and a_0=1 can be used. This implies that there is no compensation in scores for the varying economic conditions and ages of the population. For a compensated ranking with a hypothetical parity in economic and age factors of the populations, we use a varying G given by the per capita GDP-PPP of the country, and an a_0 given by the ratio of the fraction of the senior population globally and the fraction of seniors within the country. This leaves us with the values of only the constants D_0 and p_0 to be assigned. As mentioned earlier, the fatality rates are a strong function of the age group, and the measured infection fatality rates using sero-surveys have varied from negligible values to 1.2% depending on the age distribution of the sampled population [5]. The median fatality rates were 0.24%, and we use a value of 0.3% representing the global age distribution to arrive at a D_0 of 3000 deaths per million. Similarly, the maximum value of p suggested by the World-Health-Organization (WHO) is 0.1 beyond which tests become increasingly useless in breaking chains of transmission, and we use 0.1 as the half life p_0 for tests. Due to this additional exponential term, only half of the listed countries with poor testing rates or a large number of deaths, get notably corrected correspondingly in the scores for the effectiveness of the vaccines and tests. But this adds to the robustness of the ranking list to noise and unproductive mitigation efforts.

4. A study on the ranking list for robustness to noisy data

Ranking problems can be of many kinds; ranking inter-connected objects represented by a graph is the most well-known among them and is used in ranking pages on the world-wide-web [31, 32, 33]. The other common problem is the determination of an effective ranking of items when only pair-wise rankings are provided, and this is significant for generating ranking-tables in sports [34]. A third type may involve ranking items based on multiple ranking lists provided [35], representing a market survey for example. Our problem here in studying robustness is more straight-forward and is amenable to a more precise definition. Given a list of countries, a n-dimensional vector $\hat{R}$ with natural numbers 1 to n can be used to represent their rankings. Let $\Delta\hat{R}$ be the change in the ranking vector due to change in the inputs of the scoring formula. We compensate for the (potential) under-reported deaths depending on the noise levels expected in the data. Similarly, the reported number of tests are expected to be an overestimate of the actual productive tests performed, and hence deflated as well. Note that these are independent errors accrued in countries governed by different institutions and can be represented by random numbers multiplied to the reported data. Note that if data from all the countries included the same level of reporting errors, the rankings do not change and this analysis would be unnecessary. We are interested in evaluating the reliability of the rankings by determining a vector $\Delta\hat{R}$ that has the *maximum* l_1-norm, given the magnitude of changes expected in the scores F. The l_1-norm $\|\cdot\|_1$ implies that the length of the vector $\Delta\hat{R}$ representing the change in ranking list is given by the sum of absolute values of the entries i.e. $\sum_n |R_i|$ and the maximum value of $\left\|\Delta\hat{R}\right\|_1 /n$ is the maximum possible (average) change in the rank of all the n countries in the list. Note that the simple sum of the signed entries in $\Delta\hat{R}$ i.e. $\sum_n R_i$ is always zero as the increase in the rank of a country is always accompanied by an equivalent decrease of ranks of the other countries in the list. Of secondary importance, is determining vectors $\Delta\hat{R}$ that have the *maximum* l_∞-norm i.e. largest absolute value of any entry, representing the *maximum possible* change of rank of *any* country in the list.

Though it is not required for us here, a more formal mathematical statement of the problem is the following. Let the values of evaluated F_i for all countries i in the list be given by vector $\hat{F}$, and the ordinal ranks (where no two countries share the same rank even if the scores are identical) be given by a function $f : \mathbb{R}^n \longrightarrow \mathbb{N}_1^n$ with $\left\|f(\hat{F})\right\|_1 = \frac{n(n+1)}{2}$, then we are interested in:

$$\sup_{\Delta\hat{F}_i/\hat{F}_i \in \mathcal{U}(0,e)} \left\|f(\hat{F}) - f(\hat{F} + \Delta\hat{F})\right\|_p \tag{5}$$

where p is either 1 or ∞ for the two different norms, and e in the uniform distribution $\mathcal{U}$ represents the maximum possible relative error in each entry of $\hat{F}$. We study cases where e is 1 and 2 representing errors up to 100% and errors up to 200% respectively. A geometrical description of the problem and the results of analysis are described in the following figures.

In Figure 2a the rank vector $\hat{R}$ changes (in the inset figure) only for the pairs of scores given by the *shaded triangle* where $F_B > F_A$, and this becomes a possibility

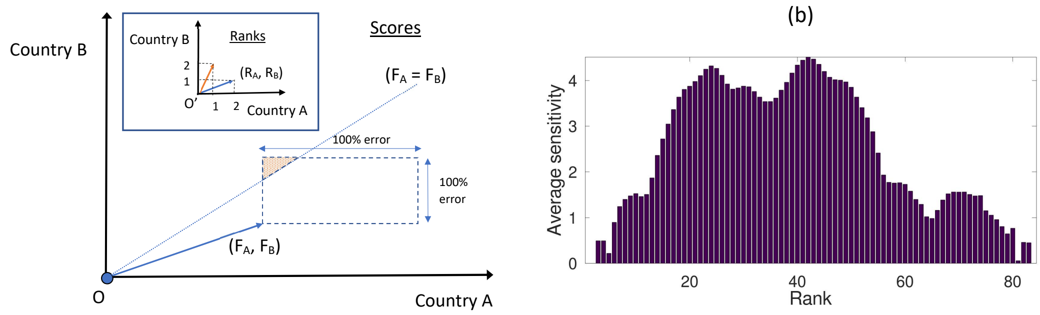

Figure 2: (a) Geometry of the problem explained using scores F of 2 countries A and B. The rank vector $\hat{R}$ changes only for the scores given by the shaded triangle where $F_B > F_A$, and this becomes a possibility in the presence of errors up to 100% in the data given by all possible scores in the rectangle. When n countries are in the ranking list, this 2D box changes to an n-D box (n-orthotope) with 2^n corners, with largest change of the ranking list given by one of these numerous corners of the box. A random sampling in the box provides the maximum change possible in the ranks with some confidence measure. (b) Average sensitivity reflected by the change in ranking due to $0-100\%$ errors at the different original ranks in the list of large countries.

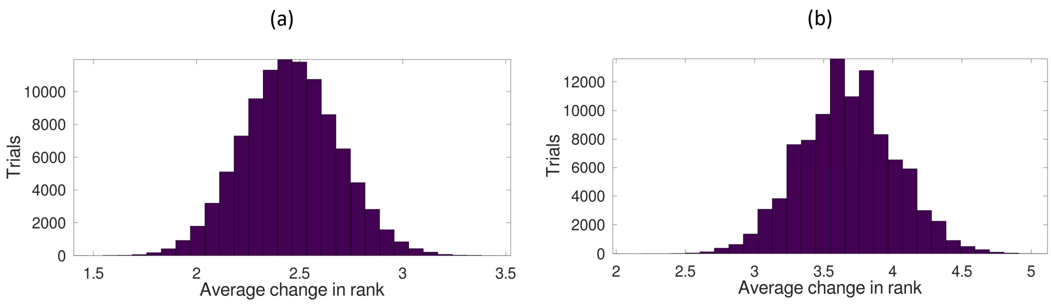

Figure 3: Histograms of average change in the ranks of the list of large countries for 10^5 random trials. Ranking list of the smaller countries is even more robust. (a) $0-100\%$ errors (b) $0-200\%$ errors

in the presence of errors up to 100% in the data given by all possible scores in the rectangle. When n countries are in the ranking list, this 2D box changes to an n-D box (n-orthotope) with 2^n corners, with largest change of ranks $\left\|\Delta\hat{R}\right\|_1$ given by one of these corners of the box. This maximum possible change of the entire ranking list i.e. maximum average change in ranks, is in general impossible to ascertain analytically, and even computationally when n is significantly larger than 20 due to the 2^n ranking lists required to be tested. The number of lists to be tested can be significantly reduced by hierarchical algorithms, but the most effective alternate approach is a random sampling of the possible ranking lists providing the maximum (average) change possible in the ranks with a confidence measure, and this is an approximate solution for eq. (5). This can be done easily using random samples with a uniform probability density in an n-box defined by the magnitude of errors, which are arbitrarily close to its corners, and such results as presented here may require only $\sim 2^{17}$ random lists to be generated. Whereas, the maximum possible change in rank for *any* country requires only the l_∞-norm i.e. $\left\|\Delta\hat{R}\right\|_\infty$, and this requires checking the maximum places any country can move if the corresponding error of 100% or 200% is added to the values of all the other $n-1$ countries in the list. This is equivalent to checking the ranking lists given by only n specific corners among the 2^n corners of the box in Figure 2a. This is relatively trivial to do and these values are correspondingly 19 and 28 ranks at most in the list of larger countries, 14 and 19 ranks respectively in the list of smaller countries, for errors up to 100% and 200%. Since these represent the stability of the rank of a single object in the list, they are not as significant as the maximum possible average change in ranks given by $\left\|\Delta\hat{R}\right\|_1/n$, which is presented in the figures for the noise expected in the data.

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