COVID-19 Vaccination Priority in the United States via Public Health's Multi-objectives Under the CDC Allocation Framework

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Abstract

To evaluate the U.S. Centers for Disease Control and Prevention's (CDC) COVID-19 vaccine prioritization strategy we developed a mathematical model that takes into account various characteristics influencing the spread and severity of the disease (age, profession, comorbidities, and living conditions). We determined the globally optimal vaccine allocation strategy for four outcomes (mortality, cases, infections, and years of life lost), and verified that the CDC strategy performed well in all outcomes although never optimally. Variation in poorly understood disease parameters did not affect the optimal allocation choice, while differences in vaccine function did. The developed global optimization approach can be used for future mass vaccination campaigns, and can be adapted for use by other countries seeking to evaluate and optimize their current prioritization strategies.

Methods and Models

We developed a compartmental disease model that stratifies the U.S. population by all characteristics included in the CDC recommendations.

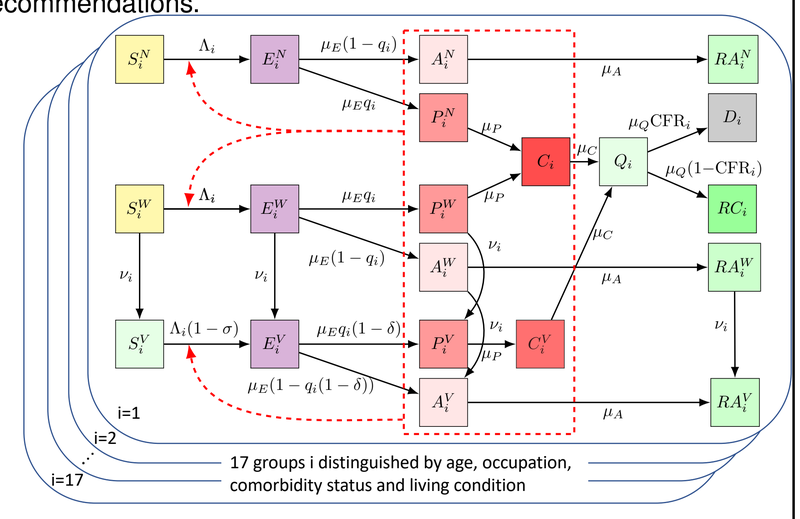


Figure 1: *Overview of the model.*

We incorporates key elements of the current pandemic including

- age-varying susceptibility to infection, β_i
- age-varying clinical fraction, q_i
- an active case-count dependent social distancing level, r(active cases)
- time-varying infectivity (accounting for the emergence of more infectious virus strains), $\phi(t)$ and
- time-varing vaccination rate, $\nu_i(t)$.

Mathematically,
$\beta_i = b_0 + b_1 \cdot$ mean age of sub-population i
$q_i = q_{75+} - \gamma \cdot$ mean difference in age between age group 75+ and sub-population i
$r(\text{active cases}) = 1 - \frac{1}{1+(\frac{c}{\log_{10}(\text{active cases})})^k}$

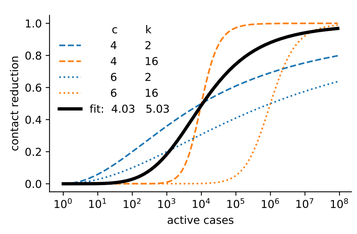


Figure 2: Case-dependent contact reduction.

$$\nu_i(t) = \frac{\xi(t)}{\sum_{\text{sub-population } k \text{ part of the current phase}} S_k^W(t)+E_k^W(t)+A_k^W(t)+RA_k^W(t)+P_k^W(t)}.$$

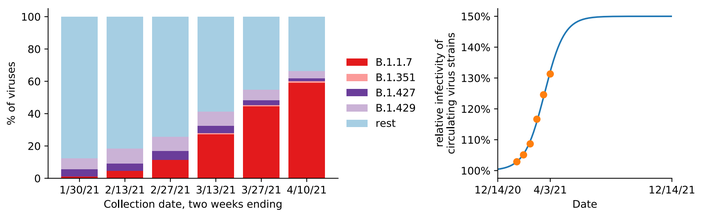


Figure 3: Time-varying infectivity of the circulating virus strains.

The force of infection for sub-population $i, i = 1,\dots,17$ at time t, is then given by $\Lambda_i = \phi(t)\big(1 - r(\text{active cases})\big)\beta_i \sum_{j=1}^{17} X_{ij}\Big(\big(f_A(A_j^N + A_j^W + f_V A_i^V) + P_j^N + P_j^W + f_V P_j^V + C_j + f_V C_j^V\big)\Big)/N_j$,

Table 1: Model parameters.

Parameter	Description
N_i	number of people in sub-population i
X_{ij}	average daily number of contacts a person in sub-population i has with sub-population j
c	log10 value of active cases at which overall contacts are reduced by 50%
k	sensitivity of contact reduction to changes in active cases (shape of the Hill function)
β_i	age-dependent susceptibility to infection
$1/\mu_E$	incubation period
q_i	age-dependent clinical fraction
$1/\mu_A$	average time of virus spread by truly asymptomatic individuals
$1/\mu_P$	average time of virus spread before symptom onset
$1/\mu_C$	average time of virus spread after symptom onset
$1/\mu_Q + 1/\mu_C$	average time between symptom onset and possible death
CFR_i	sub-population-dependent case fatality ratio
f_A	relative contagiousness of truly asymptomatic individuals
f_V	relative contagiousness of vaccinated individuals
$\xi(t)$	daily number of available vaccines
σ and δ	reduction in infections and symptomatic infections (when infected) among vaccinated (compared to non-vaccinated) individuals

Simulations and Results

Table 2: Comparison of CDC and optimal vaccine allocation strategies. *For each sub-population (characteristics and population sizes defined in the left columns) and each objective (top row), the priority phase corresponding to the optimal allocation strategy is shown. At the bottom, absolute and relative outcomes are compared for the CDC allocation and all optimal allocation strategies.*

Age	Job / living situation	Comorbidity	Number of people [millions]	Sub-population ID in model	CDC allocation	fewest deaths [thousands]	lowest YLL [millions]	fewest cases [millions]	fewest infections [millions]
0-15	NA	NA	64.71	1	4	4	4	4	4
16-64	healthcare workers	no	13.29	2	1	1	1	1	1
		yes	7.71	3	1	1	1	1	1
	frontline essential workers	no	18.98	4	2	2	2	2	2
		yes	11.02	5	2	2	2	2	2
	other essential workers	no	12.66	6	3	3	3	2	2
		yes	7.34	7	3	3	2	2	2
	remaining people	no	87.61	8	4	4	4	3	3
		yes	50.85	9	3	3	3	3	3
65-74	congested living	no	0.28	10	1	2	3	3	3
		yes	0.76	11	1	1	2	3	3
	remaining people	no	8.20	12	3	3	4	4	4
		yes	22.34	13	3	3	3	4	4
75+	congested living	no	0.39	14	1	3	3	3	4
		yes	1.57	15	1	1	2	3	4
	remaining people	no	4.07	16	2	3	4	4	4
		yes	16.47	17	2	2	3	4	4
Respective outcome of specific allocation					**CDC**	652	11.64	38.05	56.37
					fewest deaths	650.8	11.61	37.92	56.19
					lowest YLL	656.6	11.53	37.28	55.3
					fewest cases	688.3	11.81	36.59	54.17
					fewest infections	694.6	11.86	36.6	54.17
% difference in outcome between specific and respective optimal allocation					**CDC**	0.187	0.974	4.003	4.067
					fewest deaths	0	0.666	3.641	3.741
					lowest YLL	0.88	0	1.897	2.083
					fewest cases	5.754	2.437	0	0.008
					fewest infections	6.727	2.837	0.03	0

- According to the established model, there were other allocations that resulted in 0.19% lower mortality, 0.97% lower YLL, 4.0% fewer cases and 4.09% fewer infections

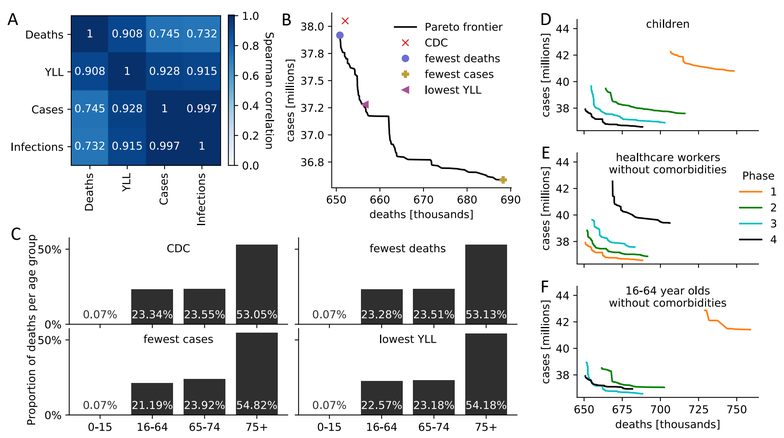


Figure 4: Comparison of CDC and optimal vaccine allocation strategies. *(A) Spearman correlation between four measures of disease burden based on a complete comparison of all 17.5 million meaningful four-phase vaccine allocation strategies. (B) Pareto frontier of all optimal strategies based on a global search of all 17.5 million meaningful vaccine allocation strategies. For strategies on the Pareto frontier, there exists no other strategy that performs better in one objective (minimizing deaths or cases) while not performing worse in the other objective. The death and case count resulting from four specific allocations is highlighted. (C) For the four strategies highlighted in (B), the distribution of all resulting deaths across the four age groups is shown as a measure of equity. (D-F) Pareto frontiers of all optimal strategies are shown when restricting (D) children, (E) healthcare workers without comorbidities, (F) 16-64 year old without comorbidities and without an essential occupation to a certain priority phase.*

- It is not possible to find a single allocation strategy that is optimal under each objective
- The CDC's allocation is better in terms of reducing mortality
- Vaccinating children in any but the last phase always led to a worse outcome

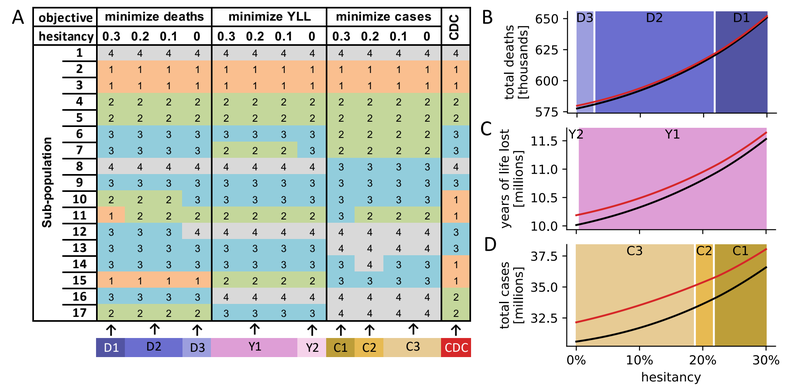
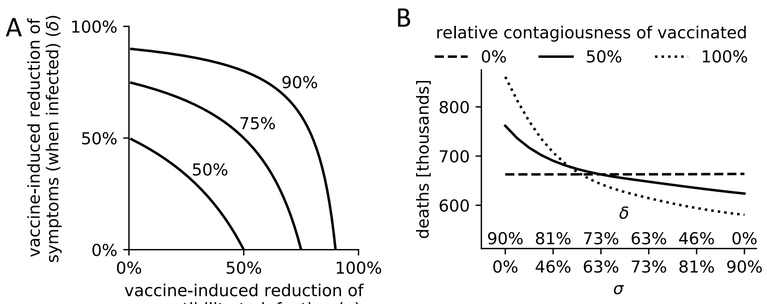


Figure 5: Dependency of findings on vaccine hesitancy. *(A) For different levels of vaccine hesitancy (30%, 20%, 10%, 0%), the optimal vaccine allocation strategies with respect to three objectives (top row) are shown, in addition to the CDC allocation. Sub-populations 1-17 are defined as in table 2. (B-D) Comparison of outcomes (total deaths (B), years of life lost (C) and total cases (D)) when using the respective optimal allocation strategy from (A; black line) and the CDC strategy (red line), for any vaccine hesitancy between 0% and 30%. The background color indicates which of the allocation strategies, identified in (A; bottom row), was optimal for a specific level of hesitancy.*

- The level of vaccine hesitancy only slightly affected optimal vaccine allocation strategies

vaccine effectiveness $= 1 - (1-\sigma)(1-\delta)$.



C

Change in phase assignment ($\sigma = 90\%$, $\delta = 0\%$ compared to $\sigma = 0\%$, $\delta = 90\%$)															
↑ later vaccination when δ = 90% ↓ earlier vaccination when δ = 90% - no change															
Sub-population	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Age	0-15	16-64								65-74				75+			
minimize deaths	-	↑	-	↑	-	-	-	-	-	-	↓	↓	↓	↓	-	-	↓
minimize YLL	-	-	-	-	↑	-	-	-	-	↓	↓	↓	↓	-	↓	↓	↓
minimize cases	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 6: Dependency of findings on vaccine function. *(A) A continuum of combinations of σ, the reduction of infections among vaccinated, and δ, the reduction of symptomatic infections among vaccinated infected individuals, can lead to a vaccine effectiveness of 50%, 75% or 90%. (B) Total deaths (y-axis) under a variety of scenarios, assuming a vaccine effectiveness of 90% and the use of the CDC allocation strategy. Scenarios differ in the relative contribution of σ and δ to the vaccine effectiveness (x-axis, see (A)), and the relative contagiousness of vaccinated individuals (compared to non-vaccinated), specified by line type (dashed: 0%, solid: 50%, dotted: 100%). (C) For three different objectives, the optimal vaccine allocation strategies are compared between two vaccines of extreme function: a vaccine that solely prevents infections ($\sigma = 90\%, \delta = 0\%$) and a vaccine that solely prevents symptoms among infected individuals ($\sigma = 0\%, \delta = 90\%$). Sub-populations (defined as in table 2) that are allocated to a later (earlier) priority phase in the latter vaccine are indicated by ↑ (↓).*

- Vaccine function didn't affect the optimal allocation while minimizing cases but it does for mortality and YLL

Discussion

- The CDC allocation strategy performed well in all considered vaccination goals but never optimally
- The CDC allocation was most similar to the optimal allocation strategy that minimizes mortality
- Not vaccinating Children in earlier phase is found optimal
- Vaccine strategies that prioritize individuals with comorbidities led to slightly better outcomes than the CDC allocation strategy
- The developed global optimization approach can be used to inform the design of future vaccine allocation strategies in the United States and elsewhere.

Note: A preprint of this work is available on MedRxiv [1].

Limitations

- We did not consider reinfection in our current model
- Sub-populations exhibit the same level of vaccine hesitancy and does not change over time
- didn't distinguished between single and double dose of vaccine
- pre-pandemic contact matrix

References

[1] Islam, Md Rafiul, et al. "Evaluation of the United States COVID-19 Vaccine Allocation Strategy." medRxiv (2021) doi 10.1101/2021.07.01.21259870

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