BMC Public Health

RESEARCH

Open Access

Amplified effect of social vulnerability on health inequality regarding COVID-19 mortality in the USA: the mediating role of vaccination allocation

Ying Chen[1*], Lanwei Zhang[2], Tenglong Li[1] and Li Li[3]

Abstract

Background: Vaccination reduces the overall burden of COVID-19, while its allocation procedure may introduce additional health inequality, since populations characterized with certain social vulnerabilities have received less vaccination and been affected more by COVID-19. We used structural equation modeling to quantitatively evaluate the extent to which vaccination disparity would amplify health inequality, where it functioned as a mediator in the effect pathways from social vulnerabilities to COVID-19 mortality.

Methods: We used USA nationwide county ($n = 3112$, 99% of the total) level data during 2021 in an ecological study design. Theme-specific rankings of social vulnerability index published by CDC (latest data of 2018, including socioeconomic status, household composition & disability, minority status & language, and housing type & transportation) were the exposure variables. Vaccination coverage rate (VCR) during 2021 published by CDC was the mediator variable, while COVID-19 case fatality rate (CFR) during 2021 published by John Hopkinson University, the outcome variable.

Results: Greater vulnerabilities in socioeconomic status, household composition & disability, and minority status & language were inversely associated with VCR, together explaining 11.3% of the variance of VCR. Greater vulnerabilities in socioeconomic status and household composition & disability were positively associated with CFR, while VCR was inversely associated with CFR, together explaining 10.4% of the variance of CFR. Our mediation analysis, based on the mid-year data (30th June 2021), found that 37.6% (mediation/total effect, 0.0014/0.0037), 10% (0.0003/0.0030) and 100% (0.0005/0.0005) of the effects in the pathways involving socioeconomic status, household composition & disability and minority status & language, respectively, were mediated by VCR. As a whole, the mediation effect significantly counted for 30.6% of COVID-19 CFR disparity. Such a mediation effect was seen throughout 2021, with proportions ranging from 12 to 32%.

Conclusions: Allocation of COVID-19 vaccination in the USA during 2021 led to additional inequality with respect to COVID-19 mortality. Viable public health interventions should be taken to guarantee an equitable deployment of healthcare recourses across different population groups.

*Correspondence: Ying.Chen01@xjtlu.edu.cn

[1] Wisdom Lake Academy of Pharmacy, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China
Full list of author information is available at the end of the article

Keywords: Social vulnerability, Health inequality, Mediation effect, COVID-19, Vaccination, Case fatality rate, Epidemiology, Ecological study, USA

Background

Health disparities due to sociodemographic factors, under the shadow of COVID-19, reveal the inadequacy of current public health strategies in achieving 'optimal health for all' [1]. The problem becomes more pronounced in developed countries where healthcare resources are relatively abundant. Communities with lower socioeconomic status have higher COVID-19 morbidity and mortality, especially in people of minority, those of working class with lower education levels, poverty, poor housing, low household incomes, overcrowded living, food insecurity, lacking health insurance and speaking a language other than the national language [2–20]. These communities require necessary interventions for a better deployment of healthcare resources, ensuring equity in access to prevention and care services across different population groups during the pandemic [1, 21].

As an effective way to reduce new and more severe cases [22–25], vaccination provides hope that the pandemic may end and normalize life by reducing new infections and clinical severity. The WHO Europe Health 2020 policy framework prioritizes equitable access to vaccination [26]. The USA has a framework for equitable allocation of COVID-19 vaccine [27, 28]. However, a growing body of literature has shown that lower COVID-19 vaccination coverage rates (VCRs) are common in social vulnerable populations [28–38]. The reasons are multifold. Vaccine hesitancy may be one of the barriers [38–40]. Furthermore, structural barriers, such as language, transportation, computer/internet access, immigrant status, and long distances to local healthcare facilities, may also play important roles [35, 41]. Inequality in vaccination coverage is a particular concern, especially since socially vulnerable populations already have been disproportionately affected by COVID-19 [2–20].

COVID-19 vaccination is vital in the reduction of COVID-19 disease burden [42]. However, vaccination implementation may exacerbate health inequality since communities with certain social vulnerabilities also have lower VCRs. We, therefore hypothesized, that the association of social vulnerability status with COVID-19 outcomes would be amplified by vaccination implementation, where vaccination inequality plays a significant mediator role. Identifying this issue would promote health equality during the current pandemic.

Methods

Our study uses structural equation modeling to evaluate the mediation effect potentially existing in the pathway between social vulnerability and COVID-19 mortality, based on the county-level USA data during 2021.

Data and study design

We used data from USA counties (or county equivalent) as sample units, with information in three areas: 1) the social vulnerability index (year 2018), 2) COVID-19 vaccination coverage (year 2021), and 3) COVID-19 mortality (year 2021).

The social vulnerability index (SVI, from the USA Centers for Disease Control and Prevention (CDC), 2018), which was created by the Geospatial research, Analysis & Services Program under the Agency for Toxic Substances and Disease Registry [43]. The SVI is used by health authorities and emergency response planners identify and map the communities that need support before, during, and after a hazardous event. The SVI serves as an indicator of the relative vulnerability of every USA census tract, and it ranks the tracts in terms of 15 social factors and further groups them into four themes [44]. Percentile rankings are available for 15 individual factors. Theme-specific ranking is generated by summing the percentiles of the factors in each theme and ordering the summed percentiles. Percentile ranking is set in the range from 0 to 1, with larger values demonstrating a greater vulnerability [44]. County-level characteristics on the four SVI themes (i.e. socioeconomic status, household composition & disability, minority status & language, and housing type & transportation) are shown in Supplementary Fig. 1.

Data on the VCR of COVID-19 was extracted from the database provided by the CDC [45]. It collects reliable data (e.g. proportion who are fully vaccinated, and proportion with at least one dose) at county level for monitoring daily progress in COVID-19 vaccination (Fig. 1).

The case fatality rate (CFR) of COVID-19 (i.e. mortality rate per number of cases) in each USA county was accessed from the John Hopkins COVID-19 interactive map, a web-based dashboard to track COVID-19 in real-time on a daily basis [46, 47]. The CFR was computed based on the numbers of reported cases and deaths extracted from the interactive map [46]. County-level CFR during 2021 is shown in Fig. 1.

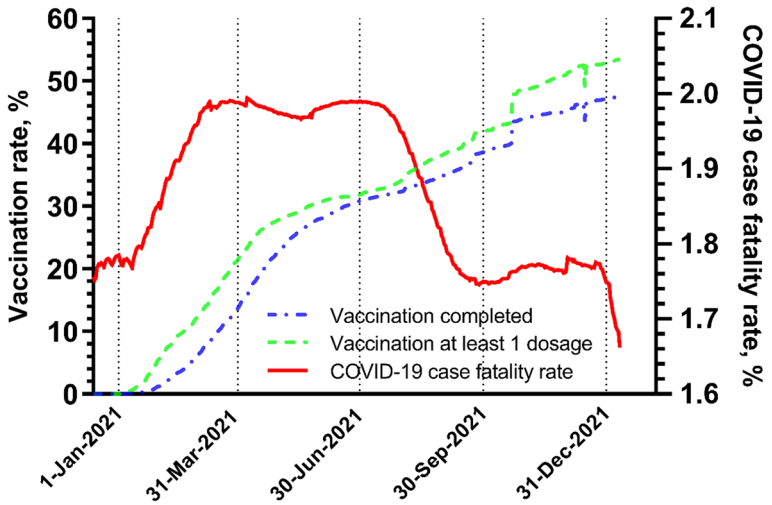

Fig. 1 The vaccination coverage rate and case fatality rate of COVID-19 in USA during 2021

Our study sample consisted of 3112 counties (out of the total 3142, 99.0%), for which all study variables were complete. The 30 counties with missing data which were excluded from our analysis were: Beaver, Box Elder, Cache, Carbon, Daggett, Duchesne, Emery, Garfield, Grand, Iron, Juab, Kane, Millard, Morgan, Piute, Rich, Sanpete, Sevier, Uintah, Washington, Wayne and Weber (in Utah), Bristol Bay, Hoonah-Angoon, Kusilvak, and Valdez-Cordova (in Alaska), Kalawao (in Hawaii), Dukes and Nantucket (in Massachusetts), and Rio Arriba (in New Mexico).

Statistical analysis

We used descriptive statistics of the studied variables (including SVI, VCR and CFR) at county level to analyse our data. For each SVI theme, we compared counties at the top half (more vulnerable, $n=1556$) with those at the bottom half (less vulnerable, $n=1556$). VCF and CFR were continuous variables within a proportional range. A simple linear regression model was first used to infer the initial association between each SVI theme and VCR. A multivariable linear regression model with backward selection, was then used to identify the final list of SVI themes associated with VCR. Similar process was done for the relationship between SVI themes and CFR. The association between VCR and CFR was also analyzed.

We hypothesized that the associations of SVI themes with CFR were mediated, at least partially, by VCR. A single-mediator model was then developed to determine the effect of SVI ('X', as exposure) on CFR ('Y', as outcome), as well as the mediating role of VCR ('M', as mediator) in the effect pathways. To estimate the effects, a series of liner regression models for constructing the structural equation modeling was carried out. Effects from 'X' to 'M' and from 'M' to 'Y' were marked as *a* and *b*, respectively. Direct effect from 'X' to 'Y' was marked as *c'*. The total effect $c=c'+a\times b$.

Associations based on the point of mid-year (30th June 2021) were reported as the main results. Validation analyses in order to question whether the findings were robust over time were conducted at the other time points on a monthly basis. Results for 31st March, 30th September and 31st December were also reported in a detailed way. The trends of effects during 2021 were summarized based on mediation analysis.

We set the level of statistical significance as 0.001 in all analyses, in order to report conservatively significant estimates of associations discovered over time. The statistical analyses were carried out in STATA 15.

Results

On 30th June 2021, based on the county-level data, on average 30.8% of the USA population was fully vaccinated, while the case fatality rate (CFR) was 2.0% (Fig. 1, and Supplementary Table 1).

Greater vulnerabilities in socioeconomic status, household composition & disability, and minority status & language were found to be inversely associated with vaccination coverage rate (VCR) in simple regression models (left, Table 1), and these associations remained significant after adjusting for each other in the final multivariable regression analysis. Together, the four SVI themes explained 11.3% of the variance of VCR (right, Table 1).

Greater vulnerabilities in socioeconomic status and household composition & disability were positively associated with CFR in simple regression models (Table 2,

Table 1 Association of social vulnerability index (SVI) with vaccination coverage rate (VCR) of COVID-19 (fully vaccinated, based on the data of 30th June 2021)

	Simple regression analyses		Multiple regression analysis	
	Regression coefficient (99.9% confidence intervals)	R^2 (for individual variables)	Regression coefficient (99.9% confidence intervals)	R^2 (for the whole model)
Individual variable				
Socioeconomic status (greater vulnerability)	-0.0995 (-0.1167, -0.0822)	0.1035	-0.0851 (-0.1051, -0.0652)	-
Household composition & disability (greater vulnerability)	-0.0621 (-0.0799, -0.0442)	0.0401	-0.0199 (-0.0395, -0.0002)	-
Minority status & language (greater vulnerability)	-0.0429 (-0.0610, -0.0248)	0.0190	-0.0278 (-0.0452, -0.0103)	-
Housing type & transportation (greater vulnerability)	-0.0083 (-0.0265, 0.0099)	-	-	-
Model	-	-	-	0.1134

Table 2 Association of social vulnerability index (SVI) and vaccination coverage rate (VCR) of COVID-19 with case fatality rate (CFR) of COVID-19 (fully vaccinated, based on the data of 30th June 2021)

	Simple regression analyses		Multiple regression analysis	
	Regression coefficient (99.9% confidence intervals)	R^2 (for individual variables)	Regression coefficient (99.9% confidence intervals)	R^2 (for the whole model)
Individual variable				
Social vulnerability index				
Socioeconomic status (greater vulnerability)	0.0048 (0.0037, 0.0060)	0.0575	0.0023 (0.0010, 0.0036)	-
Household composition & disability (greater vulnerability)	0.0045 (0.0034, 0.0057)	0.0512	0.0027 (0.0014, 0.0039)	-
Minority status & language (greater vulnerability)	0.0003 (-0.0009, 0.0014)	-	-	-
Housing type & transportation (greater vulnerability)	0.0005 (-0.0007, 0.0017)	-	-	-
Vaccination coverage rate of COVID-19	-0.0163 (-0.0200, -0.0126)	0.0631	-0.0122 (-0.0160, -0.0084)	-
Model	-	-	-	0.1044

left). VCR was also associated in an inverse way (Table 2, left). In the multivariable regression model containing these three factors, each of those associations remained significant (Table 2, right). Together, these three factors explained 10.4% of the variance of CFR (Table 2, right).

These results require further investigation of a possible mediation effect using the structural equation modeling, and a proposed diagram of impact pathways shown in Fig. 2.

To evaluate the mediation effect of VCR, we defined the effects of all pathways (including path *a*, path *b*, path *c'*, and path *c*) based on the data of 30th June 2021 (Table 3). Both socioeconomic status and household composition & disability had direct effects (path *c'*) on CFR of COVID-19, after adjusting for VCR. Compared with the counties ranked in the less vulnerable half those in the more vulnerable half in the themes of socioeconomic status and household composition & disability had 0.23% and 0.27% of increases in CFR, respectively (Table 3). Furthermore, via the mediation pathway (path $a \times b$) by VCR, these two social vulnerability factors had indirect effects on CFR (0.14% and 0.03%, respectively, Table 3). Thus, the total effects (path *c*) of socioeconomic status and household composition & disability on CFR were 0.37% and 0.30%, respectively (Table 3). For minority status & language, there was no significant direct effect (path *c'*), but a small effect (0.05%) was observed in the mediation pathway (path $a \times b$) (Table 3).

Overall, based on the data of 30th June 2021, three SVI themes (i.e. socioeconomic status, household composition & disability, and minority status & language) were found to be associated with CFR, where VCR played a mediator role. Approximately 30.6% of the total effect can be attributed to the mediation effect of VCR (Table 3).

The mediation effect of VCR could be confirmed throughout 2021, although the estimated effect sizes varied from time to time and they tended to be smaller in the latter part of 2021 (Fig. 3, and Supplementary Tables 2, 3 and 4).

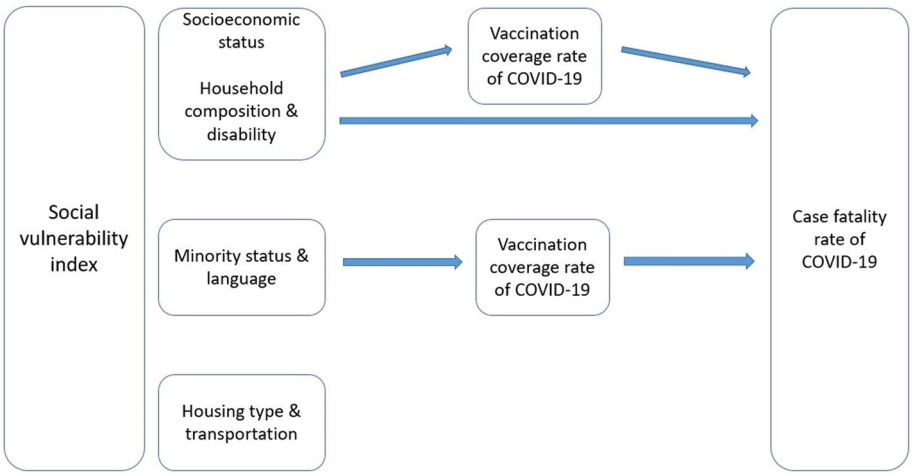

Fig. 2 Vaccination coverage rate as a mediator in the impact pathway between certain themes of social vulnerability index and case fatality rate of COVID-19

Table 3 Quantification of mediation effects (based on the data of 30th June 2021)

	By social vulnerability index domain			Overall
	Socioeconomic status	Household composition & disability	Minority status & language	
Path *a*: (X > M)	-0.0851	-0.0199	-0.0278	-
Path *b*: (M > Y)	-0.0163	-0.0163	-0.0163	-
Indirect effect (*a* × *b*: X > M > Y)	0.0014	0.0003	0.0005	0.0022
Direct effect (Path *c'*: X > Y adjusted for M)	0.0023	0.0027	-	0.0050
Total effect (Path *c*: X > Y)	0.0037	0.0030	0.0005	0.0072
Mediated (*a* × *b*/*c*), %	37.8	10.0	100.0	30.6

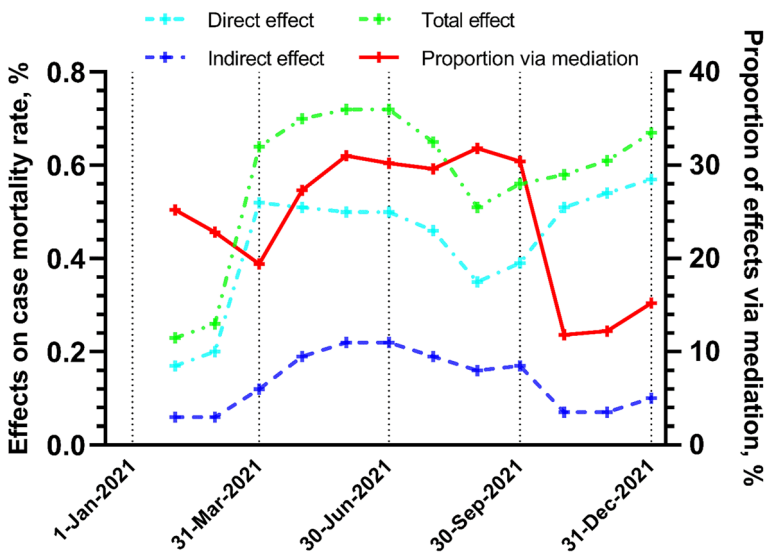

Fig. 3 The direct, mediation (indirect) and total effects calculated monthly over the year of 2021

Discussion

The COVID-19 pandemic continues to be a global crisis in public health since the initial outbreak in 2019. Previous research has shown that populations with social vulnerability are associated with severer disease outcomes [2–19]. We hypothesized that, after the introduction of COVID-19 vaccination, such an association would be amplified since socially vulnerable people are less likely to be vaccinated [28–38]. By using mediation analysis, our results confirmed our hypothesis showing that inequality of vaccination allocation was the mediator of the social vulnerability-health inequality association.

We used the theme-specific social vulnerability index (SVI) which included four themes: socioeconomic status, household composition & disability, minority status & language, and housing type & transportation to investigate their relationships with mortality rate per number of cases of COVID-19. Our results were consistent with previous research which reported that incidence and mortality rates of COVID-19 were disproportionately higher in the USA counties with greater social vulnerability [18, 48]. The magnitudes of impacts varied significantly across different themes of social vulnerability. Using county level data for 2020, Karaye and Horney showed that COVID-19 incidence was associated with household composition & disability, minority status & language and housing type & transportation, and the theme of minority status & language had the strongest impact on COVID-19 incidence [48]. Our results identified socioeconomic status and household composition & disability as the two most influential themes for COVID-19 mortality.

Vaccination is helpful for reducing the overall burden of COVID-19 [42]. However, disparities in vaccination by social vulnerability have been recorded since the beginning of the USA's COVID-19 vaccination campaign in December 2020 [28–37, 49]. We analysed and reported the data from the beginning of vaccination campaign, to depict the timely trend in vaccination disparities. Our mediation analysis showed that additional effects of social vulnerabilities on case fatality rate (CFR) was mediated by vaccination coverage rate (VCR). Across the four social vulnerability themes, the largest mediation effect was found in the 'socioeconomic status (lower socioeconomic status – lower vaccination coverage – higher case fatality rate)' pathway, followed by the pathways of 'household composition & disability' and 'minority status & language'. Interestingly, the effect of minority status & language on COVID-19 CFR was mainly attributed to mediation as no direct effect was detected, revealing the essential role of VCR in this pathway.

Health inequalities often surface when the structure of a society is affected by a new disease or disease prevention and control measures which benefit only certain communities [4]. People with lower socioeconomic status are less likely to undertake social distancing since they are typically identified as having jobs as essential workers or labourers [50]. They tend to live and work in crowded places, having less protection against COVID-19 [50]. These people may take more time to understand the disease and ways to protect themselves, especial due to lower educational levels [51, 52]. Communities with more econmonic resource and better infrastrucutre are likely better prepared for COVID-19 prevention and care [15, 16, 20, 28, 37]. Communities with social disadvantage were assoicated with fewer beds per number of residents in New York City [53]. A Brazilan study showed that the level of health-system readiness and response to COVID-19 was largely dependent on the socieconomic status of individual communities across the country [54]. Especially, when novel health interventions such as vaccines are implemented in limited supply, it is resulted in competition among individuals or communities, favoring those of higher socioeconomic status [28, 37].

The UK Scientific Advisory Group for Emergencies identified four barriers to COVID-19 vaccine uptake among ethnic minority groups: inconvenience and access barriers (e.g. cost, time and distance to access vaccine), context and socio-demographic variation (e.g. lower uptake among people with low levels of education), low trust and confidence (in vaccine efficacy and safety), and lower perception of disease risk [55]. Similarly, those aforementioned structural barriers (or similar barriers), together with vaccine hesitancy, led to the low vaccine uptake among ethnic minority groups in the USA [41, 56]. By September 2021, over 75% of adults in the USA had received at least one dose of COVID-19 vaccine, however, the proportions of vaccinated adults were less than 20% in Hispanic/Latino and black populations [41]. We have shown that insufficient English language skills and mobility restriction (e.g. disability) are also important barriers. In order to promote the vaccination equity in society, the public should acknowledge that sociocultural tailored approaches are needed to engage particular groups and build trust [40]. These path-dependency-breaking measures can be coupled with optimized vaccine accesses, such as optimized spatial arrangement of vaccination venues in socially disadvantaged neighborhoods, to promote vaccine uptake among social vulnerable groups [40].

Link and Phelan developed the theory of 'fundamental causes' to explain the relationship between social conditions and health inequalities [57, 58]. In this theory, diseases transition through four phases over a period: 1) natural mortality, characterized by no knowledge about risk factors, preventions, or treatments for a disease in a

population; 2) producing inequalities, characterized by unequal diffusion of innovations; 3) reducing inequalities, characterized by increased access to health knowledge; and 4) reduced mortality/disease elimination, characterized by widely available prevention and effective treatment [59]. We discovered a significant mediator role of vaccination coverage rate (VCR) throughout 2021, however, the mediation effect tended to be smaller after September. Our observation to some extent supports this theory. We suggest that the initiation of vaccination, as a new protective method from COVID-19 death, produces additional inequality on top of the existing difference in social vulnerability. After a period of time, due to increased access to vaccine (e.g. increased vaccine supply), the additional inequality starts to diminish. However, this evolving trend of mediation effect during 2021 may also be influenced by the health determinants of COVID-19 CFR, as these factors (including virus variants) were dynamic over time [3]. We suggest that longitudinal monitoring data should be used to record and interpret these temporal trends.

To develop adaptive public health countermeasures, it is helpful to identify any tipping point or time lag between the intervention measures e.g. VCR and the health responses e.g. COVID-19 CFR. For instance, when the full vaccination rate reached 30% in July, the CFR started to drop from 2.0%, and leveled off at 1.8% from September until December (Fig. 1). Subsequently, a turning point of vaccination's mediation effect occurred around September, followed by a decreasing mediation effect (measured by the proportion of mediation effect out of total effect) from 35 to 12% in two months (Fig. 3). The rapid shift in public health responses requires speedy public health workforce action to take place in narrow time window [60]. Sentinel studies may be useful to interpret system change signals and identify priorities for actions to ensure social equity of healthcare resource [49].

The COVID-19 pandemic may further exert impact on social and health inequalities in many aspects and in the long-term [61]. COVID-19 is known to occur at increased risk and result in more severe outcomes for individuals who have multiple comorbidities [61]. Furthermore, there is growing concern about the post-COVID-19 syndrome which is more likely to affect those who were already disadvantaged [62].

Our study does have a few limitations. Firstly, we focused only on social vulnerability, vaccination allocation and COVID-19 mortality, but additional information that may have influenced the studied relationships, such as other regional specific county factors was not included. Secondly, we used an ecological study design, so possible bias due to factors such as migration may have an impact. However, since the COVID-19 pandemic is new, such bias should be minor within a relative short duration. Thirdly, we were unable to rule out potential reporting bias that may exist across different counties, although the data we used may be considered to be of a quality [43–46].

We have demonstrated that by using mediation analysis based on USA county level data during 2021, we discovered an amplified effect of social vulnerability in health inequality on COVID-19 mortality, which may be attributed to the mediation effect of vaccination allocation across different counties.

Conclusions

We have demonstrated that health inequality and its driving factors should be explored by public health policymakers, practitioners, and clinicians. Efforts should be made to narrow the health disparities by identifying and supporting socially vulnerable populations. Furthermore, when implementing a novel preventive measure such as vaccines, it is important to ensure equitable access to different social groups, thus preventing further amplification in health inequality. We suggest that future work should be done at the community level, possibly with targeted interventions, to develop viable countermeasures to any amplified health system inequality which may arise.

Abbreviations

CDC: Centers for Disease Control and Prevention; CFR: Case Fatality Rate; COVID-19: Coronavirus Disease 2019; SVI: Social Vulnerability Index; USA: United States of America; VCR: Vaccination Coverage Rate; WHO: World Health Organization.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-022-14592-w.

Additional file 1: Supplementary Figure 1. Graphical maps of the Social Vulnerability Index 2018 by themes at the county level in USA. **Supplementary Table 1.** Vaccination coverage rate of COVID-19, and case fatality rate of COVID-19 at the county level of USA on 31stMarch, 30th June, 30thSeptember, and 31st December 2021. **Supplementary Table 2.** Association of social vulnerability index with vaccination coverage rate of COVID-19 (fully vaccinated, based on the data of 31st March 2021, 30th September 2021, and 31st December 2021). **Supplementary Table 3.** Association of social vulnerability index and vaccination coverage rate of COVID-19 with case fatality rate of COVID-19 (fully vaccinated, based on the data of 31st March 2021, 30th September 2021, and 31st December 2021). **Supplementary Table 4.** Quantification of medication effects (based on the data of 30th March 2021, 31st September 2021, and 31st December 2021).

Acknowledgements

The authors thank the other colleagues at the Wisdom Lake Academy of Pharmacy, Xi'an Jiaotong-Liverpool University for their academic and administrative support. YC would like to express his special appreciation for the arrival of

his baby daughter, with whom the process of manuscript writing has become a particularly memorable and enjoyable moment.

Authors' contributions
YC and LL conceived the study. LZ, YC and TL analyzed the data. YC and LL drafted the initial manuscript. YC and LZ had equal contribution to the paper. All authors contributed to the study design and interpretation of the data, and all authors approved the final version of the manuscript submitted for publication.

Funding
No funding was received for conducting this study.

Availability of data and materials
SVI (2018), created by the Geospatial research, Analysis & Services Program under the Agency for Toxic Substances and Disease Registry, was publicly accessible at https://www.atsdr.cdc.gov/placeandhealth/svi/documentation/SVI_documentation_2018.html. Data on the VCR of COVID-19 was extracted from the database provided by the USA CDC at https://data.cdc.gov/Vaccinations/COVID-19-Vaccinations-in-the-United-States-County/8xkx-amqh. CFR of COVID-19 in each USA county was obtained from the University of John Hopkinson, a web-based dashboard to track COVID-19 in real-time on a daily basis, at https://github.com/CSSEGISandData/COVID-19.

Declarations

Ethics approval and consent to participate
This study was conducted in accordance with the principles of the Helsinki Declaration.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author details
[1]Wisdom Lake Academy of Pharmacy, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China. [2]Department of Biology, School of Science, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China. [3]Department of Health and Environmental Sciences, School of Science, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China.

Received: 7 June 2022 Accepted: 10 November 2022
Published online: 19 November 2022

References

1. Ford CL. Commentary: addressing Inequities in the Era of COVID-19: the pandemic and the urgent need for critical race theory. Fam Community Health. 2020;43:184–6.
2. Khanijahani A, Iezadi S, Gholipour K, Azami-Aghdash S, Naghibi D. A systematic review of racial/ethnic and socioeconomic disparities in COVID-19. Int J Equity Health. 2021;20:248.
3. Neelon B, Mutiso F, Mueller NT, Pearce JL, Benjamin-Neelon SE. Spatial and temporal trends in social vulnerability and COVID-19 incidence and death rates in the United States. PLoS ONE. 2021;16: e0248702.
4. Clouston SAP, Natale G, Link BG. Socioeconomic inequalities in the spread of coronavirus-19 in the United States: a examination of the emergence of social inequalities. Soc Sci Med. 2021;268: 113554.
5. Whittle RS, Diaz-Artiles A. An ecological study of socioeconomic predictors in detection of COVID-19 cases across neighborhoods in New York City. BMC Med. 2020;18:271.
6. Ogedegbe G, Ravenell J, Adhikari S, Butler M, Cook T, Francois F, et al. Assessment of Racial/Ethnic Disparities in Hospitalization and Mortality in Patients With COVID-19 in New York City. JAMA Netw Open. 2020;3: e2026881.
7. Tan AX, Hinman JA, Abdel Magid HS, Nelson LM, Odden MC. Association between income inequality and county-level COVID-19 Cases and deaths in the US. JAMA Netw Open. 2021;4: e218799.
8. Chakrabarti S, Hamlet LC, Kaminsky J, Subramanian SV. Association of human mobility restrictions and race/ethnicity-based, sex-based, and income-based factors with inequities in well-being during the COVID-19 Pandemic in the United States. JAMA Netw Open. 2021;4: e217373.
9. Ahmad K, Erqou S, Shah N, Nazir U, Morrison AR, Choudhary G, et al. Association of poor housing conditions with COVID-19 incidence and mortality across US counties. PLoS ONE. 2020;15: e0241327.
10. Kabarriti R, Brodin NP, Maron MI, Guha C, Kalnicki S, Garg MK, et al. Association of race and ethnicity with comorbidities and survival among patients With COVID-19 at an Urban Medical Center in New York. JAMA Netw Open. 2020;3: e2019795.
11. Karmakar M, Lantz PM, Tipirneni R. Association of social and demographic factors with COVID-19 Incidence and Death Rates in the US. JAMA Netw Open. 2021;4: e2036462.
12. Association of Social and Economic Inequality With Coronavirus Disease 2019 Incidence and Mortality Across US Counties - PubMed. https://pubmed.ncbi.nlm.nih.gov/33471120/. Accessed 7 Apr 2022.
13. Yoshikawa Y, Kawachi I. Association of socioeconomic characteristics with disparities in COVID-19 outcomes in Japan. JAMA Netw Open. 2021;4: e2117060.
14. Kimani ME, Sarr M, Cuffee Y, Liu C, Webster NS. Associations of race/ethnicity and food insecurity with COVID-19 infection rates across US Counties. JAMA Netw Open. 2021;4: e2112852.
15. Stokes AC, Lundberg DJ, Elo IT, Hempstead K, Bor J, Preston SH. COVID-19 and excess mortality in the United States: a county-level analysis. PLoS Med. 2021;18: e1003571.
16. Krieger N, Waterman PD, Chen JT. COVID-19 and overall mortality inequities in the surge in death rates by zip code characteristics: Massachusetts, January 1 to May 19, 2020. Am J Public Health. 2020;110:1850–2.
17. Gaglioti AH, Li C, Douglas MD, Baltrus PT, Blount MA, Zahidi R, et al. Population-level disparities in covid-19: measuring the independent association of the proportion of black population on COVID-19 cases and deaths in US Counties. J Public Health Manag Pract. 2021;27:268–77.
18. Islam SJ, Nayak A, Hu Y, Mehta A, Dieppa K, Almuwaqqat Z, et al. Temporal trends in the association of social vulnerability and race/ethnicity with county-level COVID-19 incidence and outcomes in the USA: an ecological analysis. BMJ Open. 2021;11: e048086.
19. Tieskens KF, Patil P, Levy JI, Brochu P, Lane KJ, Fabian MP, et al. Time-varying associations between COVID-19 case incidence and community-level sociodemographic, occupational, environmental, and mobility risk factors in Massachusetts. BMC Infect Dis. 2021;21:686.
20. Macharia PM, Joseph NK, Okiro EA. A vulnerability index for COVID-19: spatial analysis at the subnational level in Kenya. BMJ Glob Health. 2020;5: e003014.
21. Smith JA, Judd J. COVID-19: Vulnerability and the power of privilege in a pandemic. Health Promot J Austr. 2020;31:158–60.
22. Patel MD, Rosenstrom E, Ivy JS, Mayorga ME, Keskinocak P, Boyce RM, et al. Association of simulated COVID-19 vaccination and nonpharmaceutical interventions with infections, hospitalizations, and mortality. JAMA Netw Open. 2021;4: e2110782.
23. Tenforde MW, Self WH, Adams K, Gaglani M, Ginde AA, McNeal T, et al. Association Between mRNA Vaccination and COVID-19 Hospitalization and Disease Severity. JAMA. 2021;326:2043–54.
24. Baden LR, El Sahly HM, Essink B, Kotloff K, Frey S, Novak R, et al. Efficacy and Safety of the mRNA-1273 SARS-CoV-2 Vaccine. N Engl J Med. 2021;384:403–16.
25. Polack FP, Thomas SJ, Kitchin N, Absalon J, Gurtman A, Lockhart S, et al. Safety and Efficacy of the BNT162b2 mRNA Covid-19 Vaccine. N Engl J Med. 2020;383:2603–15.
26. World Health Organization. Regional Office for Europe, Health 2020: a European policy framework and strategy for the 21st century. Copenhagen: World Health Organization. Regional Office for Europe, 2013. [Online]. Available: https://apps.who.int/iris/handle/10665/326386
27. Committee on Equitable Allocation of Vaccine for the Novel Coronavirus, Board on Health Sciences Policy, Board on Population Health and Public Health Practice, Health and Medicine Division, National Academies of Sciences, Engineering, and Medicine. Framework for Equitable Allocation of COVID-19 Vaccine. Washington, D.C.: National Academies Press; 2020.

28. Hughes MM, Wang A, Grossman MK, Pun E, Whiteman A, Deng L, et al. County-Level COVID-19 Vaccination Coverage and Social Vulnerability - United States, December 14, 2020-March 1, 2021. MMWR Morb Mortal Wkly Rep. 2021;70:431–6.
29. Thakore N, Khazanchi R, Orav EJ, Ganguli I. Association of social vulnerability, COVID-19 vaccine site density, and vaccination rates in the United States. Healthc (Amst). 2021;9: 100583.
30. Donadio G, Choudhary M, Lindemer E, Pawlowski C, Soundararajan V. Counties with lower insurance coverage and housing problems are associated with both slower vaccine rollout and higher COVID-19 incidence. Vaccines (Basel). 2021;9:973.
31. Pingali C, Meghani M, Razzaghi H, Lamias MJ, Weintraub E, Kenigsberg TA, et al. COVID-19 Vaccination Coverage Among Insured Persons Aged ≥16 Years, by Race/Ethnicity and Other Selected Characteristics - Eight Integrated Health Care Organizations, United States, December 14, 2020-May 15, 2021. MMWR Morb Mortal Wkly Rep. 2021;70:985–90.
32. Bruckhaus AA, Abedi A, Salehi S, Pickering TA, Zhang Y, Martinez A, et al. COVID-19 Vaccination Dynamics in the US: coverage velocity and carrying capacity based on socio-demographic vulnerability indices in California. J Immigr Minor Health. 2021. https://doi.org/10.1007/s10903-021-01308-2.
33. Brown CC, Young SG, Pro GC. COVID-19 vaccination rates vary by community vulnerability: a county-level analysis. Vaccine. 2021;39:4245–9.
34. Whiteman A, Wang A, McCain K, Gunnels B, Toblin R, Lee JT, et al. Demographic and social factors associated with COVID-19 Vaccination Initiation among adults aged ≥65 Years - United States, December 14, 2020-April 10, 2021. MMWR Morb Mortal Wkly Rep. 2021;70:725–30.
35. Wang H, Xu R, Qu S, Schwartz M, Adams A, Chen X. Health inequities in COVID-19 vaccination among the elderly: case of connecticut. J Infect Public Health. 2021;14:1563–5.
36. Perry M, Akbari A, Cottrell S, Gravenor MB, Roberts R, Lyons RA, et al. Inequalities in coverage of COVID-19 vaccination: a population register based cross-sectional study in Wales. UK Vaccine. 2021;39:6256–61.
37. Liao TF. Social and economic inequality in coronavirus disease 2019 vaccination coverage across Illinois counties. Sci Rep. 2021;11:18443.
38. Sina-Odunsi AJ. COVID-19 vaccines inequity and hesitancy among African Americans. Clin Epidemiol Glob Health. 2021;12: 100876.
39. Nguyen KH, Nguyen K, Corlin L, Allen JD, Chung M. Changes in COVID-19 vaccination receipt and intention to vaccinate by socioeconomic characteristics and geographic area, United States, January 6 - March 29, 2021. Ann Med. 2021;53:1419–28.
40. Khubchandani J, Macias Y. COVID-19 vaccination hesitancy in Hispanics and African-Americans: a review and recommendations for practice. Brain Behav Immun Health. 2021;15: 100277.
41. Njoku A, Joseph M, Felix R. Changing the narrative: structural barriers and racial and ethnic inequities in COVID-19 Vaccination. Int J Environ Res Public Health. 2021;18:9904.
42. McLaughlin JM, Khan F, Pugh S, Swerdlow DL, Jodar L. County-level vaccination coverage and rates of COVID-19 cases and deaths in the United States: an ecological analysis. Lancet Reg Health Am. 2022;9: 100191.
43. Flanagan BE, Hallisey EJ, Adams E, Lavery A. Measuring community vulnerability to natural and anthropogenic hazards: the centers for disease control and prevention's social vulnerability index. J Environ Health. 2018;80:34–6.
44. CDC SVI Documentation 2018 | Place and Health | ATSDR. https://www.atsdr.cdc.gov/placeandhealth/svi/documentation/SVI_documentation_2018.html. Accessed 7 June 2022.
45. COVID-19 Vaccinations in the United States,County | Data | Centers for Disease Control and Prevention. https://data.cdc.gov/Vaccinations/COVID-19-Vaccinations-in-the-United-States-County/8xkx-amqh. Accessed 7 June 2022.
46. Dong E, Du H, Gardner L. An interactive web-based dashboard to track COVID-19 in real time. Lancet Infect Dis. 2020;20:533–4.
47. Chen Y, Ma ZF, Yu D, Jiang Z, Wang B, Yuan L. Geographical distribution of trace elements (selenium, zinc, iron, copper) and case fatality rate of COVID-19: a national analysis across conterminous USA. Environ Geochem Health. 2022;:1–14.
48. Karaye IM, Horney JA. The impact of social vulnerability on COVID-19 in the U.S.: an analysis of spatially varying relationships. Am J Prev Med. 2020;59:317–25.
49. Barry V, Dasgupta S, Weller DL, Kriss JL, Cadwell BL, Rose C, et al. Patterns in COVID-19 Vaccination Coverage, by Social Vulnerability and Urbanicity - United States, December 14, 2020-May 1, 2021. MMWR Morb Mortal Wkly Rep. 2021;70:818–24.
50. VoPham T, Weaver MD, Adamkiewicz G, Hart JE. Social distancing associations with COVID-19 infection and mortality are modified by crowding and socioeconomic status. Int J Environ Res Public Health. 2021;18:4680.
51. Gomes da Silva J, Silva CS, Alexandre B, Morgado P. Education as a Predictor Factor for Knowledge of COVID-19 in Portugal. Front Public Health. 2021;9:680726.
52. Silva MJ, Santos P. The impact of health literacy on knowledge and attitudes towards preventive strategies against COVID-19: a cross-sectional study. Int J Environ Res Public Health. 2021;18:5421.
53. Douglas JA, Subica AM. COVID-19 treatment resource disparities and social disadvantage in New York City. Prev Med. 2020;141: 106282.
54. Rocha R, Atun R, Massuda A, Rache B, Spinola P, Nunes L, et al. Effect of socioeconomic inequalities and vulnerabilities on health-system preparedness and response to COVID-19 in Brazil: a comprehensive analysis. Lancet Glob Health. 2021;9:e782–92.
55. Factors influencing COVID-19 vaccine uptake among minority ethnic groups, 17 December 2020. GOV.UK. https://www.gov.uk/government/publications/factors-influencing-covid-19-vaccine-uptake-among-minority-ethnic-groups-17-december-2020. Accessed 7 Apr 2022.
56. Razai MS, Osama T, McKechnie DGJ, Majeed A. Covid-19 vaccine hesitancy among ethnic minority groups. BMJ. 2021;372: n513.
57. Link BG, Phelan J. Social conditions as fundamental causes of disease. J Health Soc Behav. 1995;35(Extra Issue):80–94.
58. Phelan JC, Link BG, Tehranifar P. Social conditions as fundamental causes of health inequalities: theory, evidence, and policy implications. J Health Soc Behav. 2010;51(S):S28–40.
59. Clouston SAP, Rubin MS, Phelan JC, Link BG. A social history of disease: contextualizing the rise and fall of social inequalities in cause-specific mortality. Demography. 2016;53:1631–56.
60. Olliaro P, Torreele E. Global challenges in preparedness and response to epidemic infectious diseases. Mol Ther. 2022;30:1801–9.
61. Atkins JL, Masoli JAH, Delgado J, Pilling LC, Kuo C-L, Kuchel GA, et al. Preexisting comorbidities predicting COVID-19 and Mortality in the UK Biobank community cohort. J Gerontol A Biol Sci Med Sci. 2020;75:2224–30.
62. Shankar R, Perera B, Roy A, Courtenay K, Laugharne R, Sivan M. Post-COVID syndrome and adults with intellectual disability: another vulnerable population forgotten? Br J Psychiatry. 2022;29:1–3.

Publisher's Note