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Original article

Neighborhood disparities in COVID-19 outcomes in New York city over the first two waves of the outbreak

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ABSTRACT

Purpose: To assess the association of neighborhood demographic and socioeconomic characteristics with COVID-19 incidence and mortality in New York City (NYC) over the first two waves of outbreak.
Methods: This retrospective study used neighborhood-level data from 177 modified ZIP code tabulation areas in NYC between March 01, 2020 and April 30, 2021.
Results: Neighborhoods that were most severely impacted in wave 1 were also more affected in wave 2. Neighborhoods with a higher percentage of seniors (≥75 years), males, Black and Hispanic population, and large-size households had higher incidence rates of COVID-19 in wave 1 but not in wave 2. Neighborhoods with higher percentage of Black and Hispanic population and lower insurance coverage had higher death rate per capita and case fatality ratio in wave 1, and neighborhoods with higher percentage of Black and Asian population had elevated case fatality ratio in wave 2. Median household income was negatively associated with incidence rate and death rate per capita but not associated with case fatality ratio in both waves. Neighborhoods with more seniors had higher death rate and case fatality ratio in both waves.
Conclusions: Neighborhood disparities in COVID-19 incidence and mortality across NYC neighborhoods were dynamic during the first two waves of outbreak.

Introduction

Since the emergence of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), it has quickly spread to more than 200 countries and territories in the world [1]. As of May 2021, over 32 million confirmed cases of coronavirus disease 2019 (COVID-19) have been reported in the United States [2]. As a major international hub and the most densely populated city in the United States, New York City (NYC) became the epicenter of this disease in April 2020, with more than 770,000 confirmed cases of COVID-19 and more than 27,000 COVID-19 confirmed deaths as of May 2021 [3]. NYC consists of five boroughs (Bronx, Brooklyn, Manhattan, Queens, and Staten Island). Each borough has unique demographic and socioeconomic characteristics, and the neighborhoods across these boroughs play important roles in explaining health disparities in NYC [4–7]. Multiple studies have examined the variation in COVID-19 hospitalization and mortality across different boroughs' neighborhoods in the first coronavirus outbreak (from roughly March to May in 2020), highlighting health disparities by age, population density, race, ethnicity, income, and insurance status [8–11]. A second wave began roughly in December of 2020 [12], which demonstrated a different pattern of impact across

Abbreviations: SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; COVID-19, coronavirus disease 2019; NYC, New York City; ZCTA, ZIP code tabulation area; DOHMH, Department of Health and Mental Hygiene; PCR, polymerase chain reaction; ICAR, intrinsic conditional autoregressive; INLA, Integrated Nested Laplace Approximation; aRR, adjusted Rate Ratios; CI, credible interval.

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boroughs' neighborhoods. The demographic and socioeconomic associations with COVID-19 incidence and mortality between these two waves [13] hold important policy lessons, because they may elucidate dynamics of health disparities as the pandemic evolved and inform public health crisis planning, preparedness, and response. This study aims to compare the associations of neighborhood demographic and socioeconomic characteristics with COVID-19 outcomes in NYC, including confirmed COVID-19 new cases and COVID-19 related deaths, across the first two waves of the outbreak.

Methods

We used the neighborhood-level data of COVID-19 cases and death counts as well as demographic and socioeconomic characteristics to assess the associations between neighborhood risk factors and COVID-19 outcomes in NYC over the first two waves of the outbreak using Bayesian hierarchical spatial negative binomial models.

Study design and data sources

This retrospective study used neighborhood-level data, including the COVID-19 outcomes and neighborhood characteristics in NYC between March 01, 2020 and April 30, 2021. Each neighborhood was defined by a residential area corresponding to a particular modified ZIP code Tabulation Area (ZCTA). The modified ZCTA geography combines census blocks with smaller populations and have been used by NYC Department of Health and Mental Hygiene (DOHMH) [14]. The COVID-19 outcome data were acquired from the NYC DOHMH Coronavirus Data GitHub [15]. The neighborhood demographics and socioeconomics information were retrieved from the US Census Bureau using the 2019 American Community Survey 5-year estimates [16]. No individual-level data were involved in the analysis.

Study periods

We separated the study periods into two waves of the coronavirus outbreak in NYC to compare the associations of neighborhood characteristics with COVID-19 outcomes in different periods. The first wave was defined as the time interval between March 01, 2020 and May 31, 2020, and the second wave was from late November/early December to April 2021 based on local news reports [12, 17]. Since NYC DOHMH made several changes to its data repository in GitHub on December 07, 2020, the second wave data used in the analysis starts on December 07, 2020 and ends on April 30, 2021. A sensitivity analysis was also conducted using data from November 01, 2020 to April 30, 2021 for the second wave. The results are similar and thus are not included.

Outcome measures

We focused on two outcomes. The first outcome was the total number of confirmed COVID-19 positive cases in a neighborhood during each wave. A new COVID-19 case was defined by a molecular test that relies on polymerase chain reaction assay in large laboratories based on the specimen collected using nasopharyngeal swabs or sputum cup. The second outcome was the total number of COVID-19 deaths in each neighborhood during each wave, reported as deaths related to COVID-19 by the NYC DOHMH.

Neighborhood characteristics

We considered a series of neighborhood characteristic factors. These factors included borough, percentage of age group (<19, 19–59, 60–74, and ≥75 years), sex (male and female), race/ethnicity (White, Black, Hispanic, Asian, and others), households size (1, 2, 3 and ≥4 members), education (with and without high school diploma), and health insurance (with and without), along with the median household income of each neighborhood.

Statistical analysis

We used Bayesian hierarchical spatial negative binomial models to assess the associations between each outcome and the neighborhood characteristics, while accounting for spatial correlations between adjacent neighborhoods using an intrinsic conditional autoregressive (ICAR) random effect for each neighborhood [18, 19]. We assumed that each outcome followed a negative binomial distribution with neighborhood and time specific rate $\mu_{i,t}$ and variance function $\mu_{i,t} + \alpha \mu_{i,t}{}^2$, where α is the over-dispersion parameter taking a positive value. We modeled the neighborhood and time specific rate $\mu_{i,t}$ as:

$$\log(\mu_{i,t}) = \log\left(\frac{E(y_{i,t})}{P_{i,t}}\right) = X_{i,t}^T \beta + u_i$$

where $y_{i,t}$ is the outcome; $P_{i,t}$ is the offset; and $X_{i,t}$ is a vector containing one and covariates for neighborhood i at time t. For the models with the total confirmed cases as the outcome, we used the neighborhood population size as the offset and modeled the cumulative incidence rate in the neighborhood. For the models with the death counts as the outcome, we included the neighborhood population size and the confirmed positive cases as the offset to estimate the death rate per capita and the case fatality ratio, respectively. Parameters β measure associations of the neighborhood characteristics with incidence rate, dealth rate, or case fatality ratio. The error term u_i is the spatially structured residual, modelled using an ICAR structure:

$$u_i | u_{j \neq i} \sim Normal\left(\frac{\sum_j u_j}{m_j}, \frac{\sigma_u^2}{m_j}\right),$$

where m_j is the number of neighborhoods which share boundaries with the ith neighborhood, and $\sum_j u_j$ is a summation of the spatially structured residuals over all m_j neighborhoods [18, 19].

For each outcome, we first fitted separate marginal models based on data in wave 1 and wave 2 with one neighborhood characteristic factor in each model. We then fitted two separate multivariable models based on the data in wave 1 and wave 2. Each model included all neighborhood characteristic factors except education, which was excluded from the multivariable model due to its collinearity with median household income. We then fitted a third multivariable interaction model, combining data in both wave 1 and wave 2, to assess whether the associations between the outcome and the neighborhood characteristics differed across the two waves of outbreak by including all the two-way interactions between the wave indicator and each neighborhood characteristic factor. We conducted sensitivity analyses by removing the spatial structure from the three multivariable models to assess whether conclusions change. We estimated the models by Integrated Nested Laplace Approximation (INLA) using the INLA package in R [20, 21], and reported adjusted Rate Ratios (aRR) and the associated 95% credible interval (CI) for each regression coefficient.

Results

Neighborhood characteristics

We analyzed data across all 177 neighborhoods in NYC, including 25 in Bronx, 37 in Brooklyn, 44 in Manhattan, 59 in Queens, and 12 in Staten Island. Supplementary Table A.1 provides the descriptive statistics of the neighborhood characteristics. Manhattan

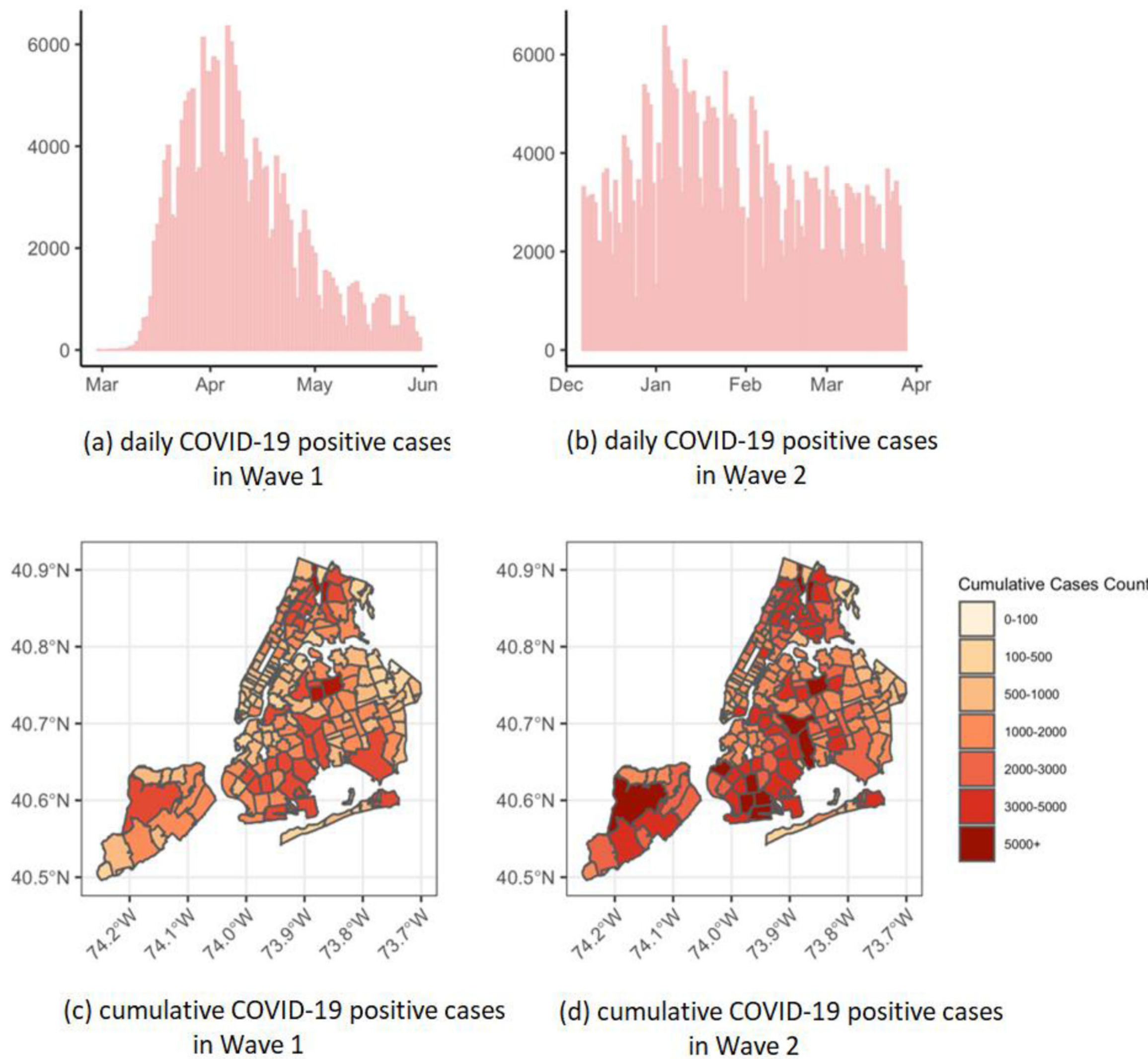

Fig. 1. Histogram of daily confirmed COVID-19 positive cases and geographical distributions of total confirmed COVID-19 positive cases in the 177 New York City ZCTAs in wave 1 and wave 2. "(For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)"

had fewer young residents aged <19 years (16%) but more residents aged 19–59 years (64%). The Bronx neighborhoods (13%) had the smallest percentage of White residents (Queens 30%, Brooklyn 38%, Manhattan 51%, and Staten Island 58%). Brooklyn (29%) and Bronx (28%) had higher percentage of Blacks; Bronx (54%) had more Hispanic; and Queens (24%) had more Asians than other boroughs. The neighborhoods in Manhattan had more households with a single member (45%), but Queens (29%) and Staten Island (33%) had more households with four or more members. The average median annual household incomes of neighborhoods were $113,000 for Manhattan, $82,000 for Queens, $81,000 for Staten Island, $65,000 for Brooklyn, and $45,000 for Bronx. The average percentage of residents with health insurance coverage were high across all the five boroughs.

Spatial and temporal patterns of COVID-19 cases and deaths

Figures 1a and b show the trend of daily COVID-19 new cases in NYC in wave 1 and wave 2, respectively. In wave 1, starting from March 2020, the daily new cases dramatically increased, peaked with more than 6000 cases per day within a month, and then slowly decreased until the end of May in 2020. Daily new cases in wave 2 also peaked at about 6500 cases per day in early January, but the daily new cases stayed above 2000 for most of days through the entire study period before mid-April. Figures 1c and d give the geographical distribution of total COVID-19 new cases in waves 1 and 2, with darker colors representing more cases in a given neighborhood. An apparent spatial disparity of total COVID-19 new cases existed across NYC neighborhoods in both wave 1 and 2, with adjacent neighborhoods displaying similar darkness. The color is darker in most of the neighborhoods in wave 2, especially in many of the neighborhoods that were hardly hit in wave 1. The spatial patterns were similar between the two waves, with a Pearson correlation coefficient of 0.73 ($P < .0001$; Supplementary Fig. A.1a) for the incidence rate in the 177 neighborhoods between the two waves.

The COVID-19 deaths in NYC peaked in mid-April 2020 at about 600 deaths per day in wave 1 (Fig. 2a). In wave 2, the COVID-19 deaths peaked at about 100 deaths per day in early February 2021 (Fig. 2b). The spatial patterns of total COVID-19 deaths in wave 1 (Fig. 2c) appeared to be consistent with total COVID-19 new cases (Fig. 1c). However, the spatial disparity of COVID-19 deaths in wave 2 (Fig. 2d) is not as prominent as in wave 1, with light color in most neighborhoods except some neighborhoods in Staten Island and South Brooklyn. Still, the death rates per capita of the 177 neighborhoods in the two waves were correlated with a Pearson correlation coefficient of 0.52 ($P < .0001$; Supplementary Fig. A.1b).

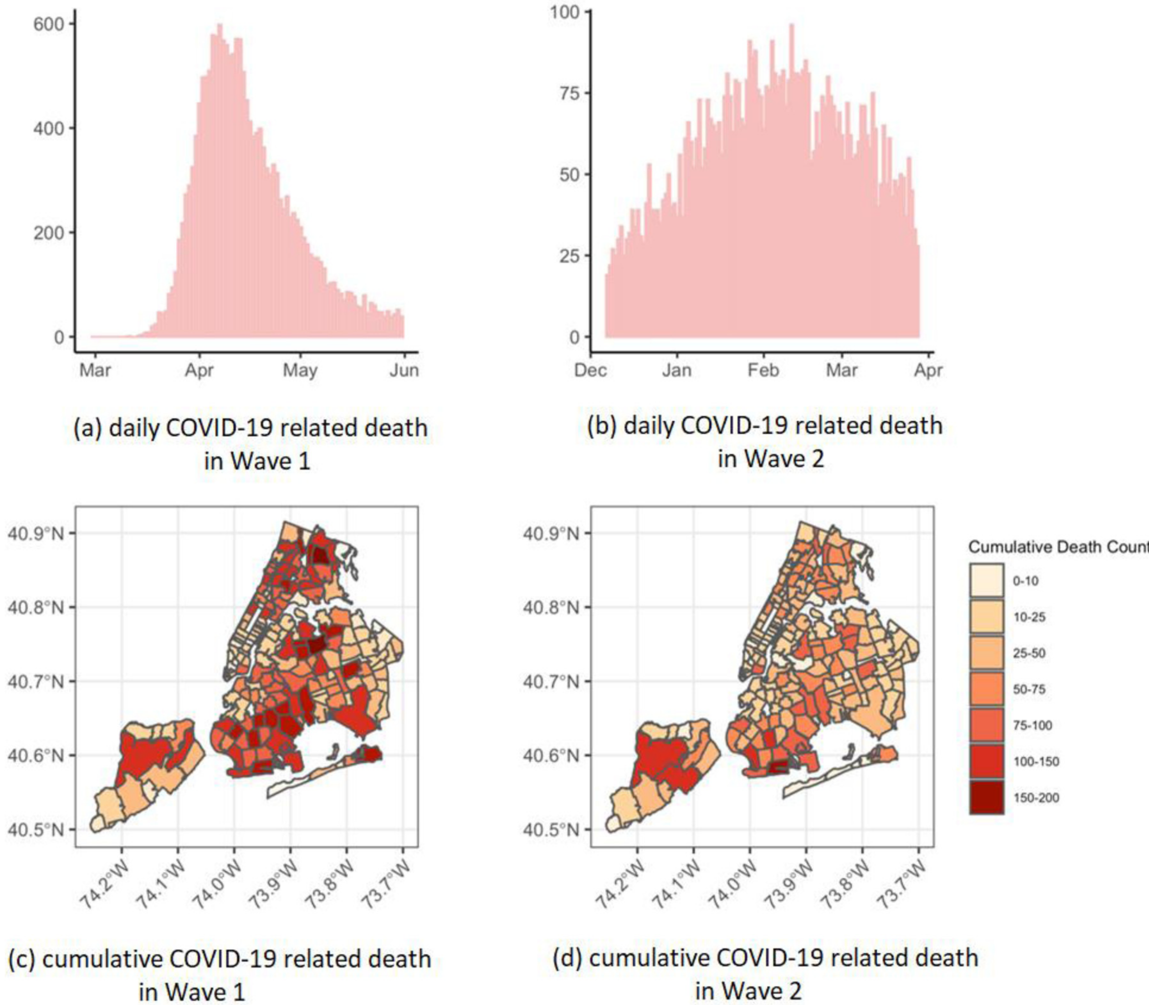

Fig. 2. Histogram of daily COVID-19 deaths and geographical distributions of total COVID-19 deaths in the 177 New York City ZCTAs in wave 1 and wave 2. "(For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)"

Neighborhood characteristics associatied with COVID-19 incidence rate

Table 1 provides the aRRs and 95% CIs of the neighborhood characteristics with significant associations with the cumulative incidence rate of COVID-19 . Compared to those who lived in Manhattan, neighborhoods in Bronx (aRR: 1.34 [95% CI: 1.14, 1.57]), Queens (aRR: 1.46 [1.25, 1.69]), and Staten Island (aRR: 1.63 [1.36, 1.94]) had higher incidence rates in wave 1, and neighborhoods in Queens (aRR: 1.24 [95% CI: 1.09, 1.40]) and Staten Island (aRR: 1.73 [95% CI: 1.50, 2.00]) also had higher incidence rates in wave 2. The incidence rates significantly decreased from wave 1 to wave 2 for neighborhoods in Queens and Bronx but not in Staten Island. Sex, age, and race/ethnicity were all significantly associated with COVID-19 incidence rates in wave 1 but not in wave 2. Specifically, for a 1% increase in the male residents, the incidence rate increased by a factor of 1.03 (95% CI: 1.01, 1.05) in wave 1. Meanwhile, for a 10% increase in the residents with age greater than or equal to 75 years, Black population, and Hispanic population, the incidence rates increased by a factor of 1.50 (95% CI: 1.26, 1.78), 1.05 (95% CI: 1.02, 1.08), and 1.06 (95% CI: 1.02, 1.11) respectively, in wave 1. Neighborhoods with more large-size households (with $\geq$4 members) had higher incidence rates in wave 1 (aRR: 1.09 [95% CI: 1.03–1.16]) but not in wave 2. Median household income was negatively associated with incidence rates in both waves, with the association slightly stronger in wave 2 than in wave 1. Every $10,000 increase in the median household income was associated with a 3% (95% CI: 2%, 5%) reduction and a 5% (95% CI: 4%, 6%) reduction in the incidence rate in wave 1 and wave 2, respectively. The interaction model shows that the associations of neighborhood charcateristics including percentage of males, greater than or equal to 75 years of age, Black population, and Hispanic population with incidence rate decreased significantly from wave 1 to wave 2.

The results of the marginal models are in Supplementary Table A.2. The conclusions are similar to the multivariable analyses; while the marginal models show bigger differences in the cumulative incidence rate between neighborhoods in Manhattan and in the other four boroughs in both waves, and stronger associations with race/ethnicity, income, household size, and health insurance. The effect of age group was no longer significant, and percentage with high school education was negatively associated with the incidence rate in both waves. The sensitivity analyses that remove the spatial structure from the multivariable models do not change the conclusions (Supplementary Table A.3).

Neighborhood characteristics associatied with COVID-19 death rate per capita

Table 2a shows the aRRs (95% CIs) of COVID-19 mortality associated with the neighborhood characteristics. Compared to neighborhoods in Manhattan, Brooklyn (aRR: 1.27 [95% CI: 1.03, 1.55])

Table 1
Results of Bayesian hierarchical spatial negative binomial models for total number of COVID-19 confirmed positive cases among 177 NYC neighborhoods during the first two waves of outbreak.

Variable	Wave 1 aRR (95% CI)	Wave 2 aRR (95% CI)	Interaction effects aRR (95% CI)
Borough			
Manhattan	Ref	Ref	Ref
Brooklyn	1.02 (0.86, 1.21)	1.00 (0.87, 1.15)	1.00 (0.87, 1.15)
Queens	**1.46 (1.25, 1.69)**	**1.24 (1.09, 1.40)**	0.88 (0.77, 1.00)
Staten Island	**1.63 (1.36, 1.94)**	**1.73 (1.50, 2.00)**	1.04 (0.86, 1.27)
Bronx	**1.34 (1.14, 1.57)**	1.07 (0.93, 1.21)	**0.82 (0.70, 0.95)**
Sex			
1% increase in males	**1.03 (1.01, 1.05)**	1.00 (0.99, 1.01)	**0.97 (0.95, 0.99)**
Age group			
10% increase in age ≥75 y	**1.50 (1.26, 1.78)**	1.06 (0.92, 1.22)	**0.65 (0.56, 0.76)**
Race/Ethnicity			
10% increase in Black	**1.05 (1.02, 1.08)**	0.98 (0.95, 1.00)	**0.92 (0.90, 0.94)**
10% increase in Asian	0.98 (0.94, 1.02)	1.01 (0.97, 1.04)	1.02 (0.98, 1.07)
10% increase in Hispanic	**1.06 (1.02, 1.11)**	1.02 (0.98, 1.05)	**0.96 (0.92, 0.99)**
Household (HH) size			
10% increase in large-size HHs with ≥4 members	**1.09 (1.03, 1.16)**	1.03 (0.98, 1.09)	0.96 (0.91, 1.01)
Health insurance			
10% increase with health insurance	1.09 (0.92, 1.28)	1.05 (0.92, 1.20)	1.02 (0.85, 1.21)
Median annual household income			
$10,000 increase	**0.97 (0.95, 0.98)**	**0.95 (0.94, 0.96)**	0.98 (0.97, 1.00)

The model used log population size as the offset to estimate incidence rate. The results are reported as adjusted Rate Ratio (aRR) and 95% credible interval (CI).

Table 2
Results of Bayesian hierarchical spatial negative binomial models for total number of COVID-19 deaths among 177 NYC neighborhoods during the first two waves of outbreak.

	aRR for death per capita (95% CI)			aRR for case fatality ratio (95% CI)		
	Wave 1	Wave 2	Interactions	Wave 1	Wave 2	Interactions
Borough						
Manhattan	Ref	Ref	Ref	Ref	Ref	Ref
Brooklyn	**1.27 (1.03, 1.55)**	1.22 (0.96, 1.54)	0.86 (0.68, 1.08)	1.09 (0.88, 1.31)	1.03 (0.87, 1.26)	0.85 (0.70, 1.02)
Queens	**1.26 (1.04, 1.53)**	1.14 (0.93, 1.39)	0.87 (0.69, 1.09)	0.97 (0.82, 1.14)	0.95 (0.81, 1.12)	0.99 (0.83, 1.19)
Staten Island	1.32 (1.00, 1.75)	**1.80 (1.42, 2.27)**	1.18 (0.85, 1.65)	0.87 (0.70, 1.08)	1.02 (0.83, 1.26)	1.12 (0.86, 1.46)
Bronx	1.07 (0.86, 1.32)	1.14 (0.93, 1.39)	0.95 (0.74, 1.22)	**0.82 (0.68, 0.97)**	1.02 (0.86, 1.21)	1.18 (0.97, 1.43)
Sex						
1% increase in males	1.02 (0.99, 1.05)	0.99 (0.97, 1.02)	0.98 (0.95, 1.01)	0.98 (0.96, 1.00)	0.99 (0.97, 1.01)	1.01 (0.98, 1.04)
Age group						
10% increase in age ≥75 y	**2.71 (2.14, 3.45)**	**2.51 (2.00, 3.16)**	1.00 (0.75, 1.33)	**1.58 (1.30, 1.93)**	**2.10 (1.76, 2.52)**	**1.38 (1.10, 1.74)**
Race/Ethnicity						
10% increase in Black	**1.08 (1.04, 1.12)**	1.00 (0.97, 1.04)	**0.94 (0.90, 0.98)**	**1.04 (1.02, 1.07)**	**1.04 (1.01, 1.07)**	1.02 (0.98, 1.05)
10% increase in Asian	0.98 (0.92, 1.04)	**1.07 (1.02, 1.13)**	1.06 (0.99, 1.14)	1.03 (0.99, 1.09)	**1.07 (1.02, 1.12)**	1.03 (0.97, 1.09)
10% increase in Hispanic	**1.09 (1.03, 1.16)**	1.04 (0.98, 1.09)	0.94 (0.88, 1.01)	1.05 (1.00, 1.10)	1.02 (0.98, 1.06)	0.98 (0.93, 1.04)
Household (HH) size						
10% increase in large-size HHs with ≥4 members	1.04 (0.97, 1.12)	1.06 (0.98, 1.15)	1.09 (1.00, 1.19)	**0.92 (0.86, 0.98)**	1.01 (0.95, 1.07)	**1.12 (1.04, 1.20)**
Health insurance						
10% increase with health insurance	**0.71 (0.55, 0.91)**	0.98 (0.80, 1.19)	**1.43 (1.07, 1.91)**	**0.71 (0.59, 0.86)**	0.97 (0.82, 1.15)	**1.40 (1.12, 1.75)**
Median annual HH income						
$10,000 increase	**0.97 (0.95, 0.98)**	**0.93 (0.92, 0.95)**	**0.96 (0.94, 0.99)**	1.00 (0.99, 1.02)	0.99 (0.97, 1.00)	0.99 (0.97, 1.00)

Model (a) used log population size as the offset to estimate death rate per capita, and model (b) used log confirmed positive cases as the offset to estimate case fatality ratio. The results are reported as adjusted Rate Ratio (aRR) and 95% credible interval (CI).

and Queens (aRR: 1.26 [95% CI:1.04, 1.53]) had higher death rates in wave 1, but Staten Island (aRR: 1.80 [95% CI: 1.42, 2.27]) had a higher death rate in wave 2. In wave 1, for a 10% increase in the residents with age greater than or equal to 75 years, Black population, and Hispanic population, the death rate per capita increased by a factor of 2.71 (95% CI: 2.14, 3.45), 1.08 (95% CI: 1.04, 1.12), and 1.09 (95% CI: 1.03, 1.16), respectively; while such increase was only observed among neighborhoods with a higher percentage of residents with age greater than or equal to 75 years in wave 2 (aRR: 2.51 [95% CI: 2.00, 3.16]). The death rate per capita increased in the neighborhoods with more Asians in wave 2 (aRR: 1.07 [95% CI: 1.02, 1.13]) but not in wave 1. Meanwhile, a 10% increase in health insurance coverage was associated with 29% (95% CI: 9%, 45%) reduction in the death rate per capita in wave 1 but not in wave 2. Every $10,000 increase in the median household income was associated with 3% (95% CI: 2%, 5%) reduction in death rate per capita in wave 1 and a 7% (95% CI: 5%, 8%) reduction in wave 2. The interactions model shows that the impact of health insurance coverage and percentage of Black population on death rate per capita decreased significantly from wave 1 to wave 2, but the impact of the median household income became slightly stronger in wave 2.

The results of the marginal models can be found in Supplementary Table A.4. All the marginal associations are significant in both waves. Compared to Manhattan, neighborhoods in all the other four boroughs had increased death rate per capita in both waves. The rate ratio decreased from wave 1 to wave 2 for Queens and Bronx but increased from wave 1 to wave 2 for Brooklyn and Staten Island. The conclusions for race/ethnicity, age, median household income, and health insurance are similar to the multivariable models, but the associations became stronger in the marginal models for all neighborhood characteristics except age and percentage of Asian population was also associated with death rate per capita in wave 1. Finally, education is not included in the multivariate model because of its collinearity with median household income. For a 10% increase in high school education, the death rate was associated with a 29% (95% CI: 23%, 35%) reduction in wave 1 and a 21% (95% CI: 15%, 27%) reduction in wave 2.

Neighborhood characteristics associatied with COVID-19 case fatality ratio

Table 2b shows the aRRs (95% CIs) of the neighborhoods characteristics with significant associations with the COVID-19 case fatality ratio. The case fatality ratios were similar across boroughs after adjusting for other factors, except for Bronx which had lower case fatality ratio than Manhattan in wave 1 (aRR: 0.82 [95% CI: 0.68, 0.97]). For a 10% increase in the residents with age greater than or equal to 75 years and Black population, the COVID-19 case fatality ratio increased by 58% (95% CI: 30%, 93%) and 4% (95% CI: 2%, 7%), respectively, in wave 1. Case fatality ratios in wave 2 were also higher in the neighborhoods with more residents greater than or equal to 75 years (aRR: 2.10 [95% CI: 1.76, 2.52]) and Black population (aRR: 1.04 [95% CI: 1.01, 1.07]). Case fatality ratio increased in neighborhoods with more Asians in wave 2 (aRR: 1.07 [95% CI: 1.02, 1.12]) but not in wave 1, and decreased in the neighborhoods with more large-size households (aRR: 0.92 [95% CI: 0.86, 0.98]) and higher health insurance coverage (aRR: 0.71 [95% CI: 0.59, 0.86]) in wave 1 but not in wave 2. The case fatality ratio was not associated with median household income in either wave 1 or wave 2. The interactions model shows that the associations of household size and health insurance coverage with case fatality ratio diminished from wave 1 to wave 2, but became stronger in wave 2 for neighborhoods with higher percentage of older adults (≥75 years).

The results of the marginal models are in Supplementary Table A.5. The conclusions were similar to the multivariable models, except for percentage of males and Asian population. The marginal models show that case fatality ratio was higher in neighborhoods with lower population of males and with higher percentages of Asian population in both waves. The sensitivity analyses that remove the spatial structure from the multivariable models do not change the conclusions (Supplementary Table A.6).

Discussion

The COVID-19 pandemic has shone a spotlight on the striking health disparities in the United States. Dominant narratives about why these disparities exist range from structural factors (e.g., public-facing employment, overcrowed housing, multigenerational housing, and densely populated residential neighborhoods) to behavioral factors (eg, differential risk assessment and risk taking among dominant vs. minority groups) [22, 23]. The evolution of health disparities in the COVID-19 incidence and mortality rates, as reported in this study, could help advance our understanding of the role that specific neighborhood-level demographic and socioeconomic factors play in different phases of the pandemic and in different health outcomes, and inform public health crisis planning, preparedness, and response [22].

In New York, public-facing workers, those living in densely populated neighborhoods, and those living in overcrowded, multigenerational housing appeared to be more impacted in the first wave [24]. This is consistent with the narrative that structural factors are most important [23, 25]. By the second wave, socioeconomic status became the dominant risk factor for both infection and mortality per capita even as the government provided additional economic support. Socioeconomic disadvantage not only produces structural factors, but also produces toxic stress, thereby adversely impacting behaviors related to executive function [26, 27]. For example, the brain's ability to plan and execute tasks tends to be damaged by the neurotoxic effects of glucocorticoids on the orbitofrontal cortex. This reduced "executive function" might explain why severely disadvantaged populations have both a difficult time getting a job and a difficult time enrolling in social benefits programs, including those that put participants on the "radar" for stimulus check receipt [28]. By reducing employment, the effect of toxic, poverty-associated stress on executive function may paradoxically mitigate exposure to COVID-19 early the pandemic among low-income populations. However, damage to the orbitofrontal cortex can also alter risk taking behaviors. As the pandemic wears on, therefre, increased risk-taking coupled with lower stimulus receipt could plausibly contribute to both exposure to COVID-19 and adverse health outcomes associated with infection [27].

We find that neighborhoods with a higher percentage of Black and Hispanic populations had a higher incidence rate and death rate per capita relative to predominantly white neighborhoods in wave 1 but not in wave 2. Moreover, the incidence rate of COVID-19 was higher in neighborhoods with higher percentage of males, older adults (≥75 years), and large-size households (≥4 members) in wave 1 but not in wave 2. These findings suggest that, neighborhoods at higher risk of morbidity and mortality were less affected by the second wave of the pandemic than the first wave. This may be explained by the changes in the risk perception and protective behavior among residents in these neighborhoods to better protect themselves from infection [29]. However, future qualitative research is needed in this area.

We find little evidence that immunity impacted zip-code-level risk of disease in wave 2 at the neighborhood level. First, the neighborhoods that were most severely impacted in wave 1 were also more affected in wave 2 despite having a higher prevalence of serum antibodies to SARS-CoV-2 [30]. At the borough level, Queens, Staten Island, and the Bronx had a higher rate of COVID-19 cases than wealthier Manhattan in wave 1. The differences of Queens and the Bronx with Manhattan were smaller in wave 2, but in Staten Island, a predominantly lower-income Republican area, the rate of COVID-19 cases and death per capita became more pronounced in wave 2. This may be explained by plausible exposure to disinformation about the disease in Staten Island [31].

We also find that neighborhoods with higher health insurance coverage rate had lower death rate per capita and case fatality ratio in wave 1, even although these neighborhoods had similar rates of COVID-19 cases compared to the other neighborhoods. Such disparity in outcomes associated with health insurance covereage was not observed in wave 2. In New York City, health insurance rates are very high due to high levels of Medicaid coverage, which is typically provided on first contact with a major medical center [32]. Because of the ubiquity of Medicaid coverage, including for the foreign-born, health insurance coverage may serve as a proxy for nearby high quality health services that enroll patients in Medicaid. For example, undiagnosed depression in NYC is associated with distance from a major medical center more than insurance status [33]. In addition, neighborhoods with higher percentage of Black population had higher case fatality ratio in both waves, a group that generally lives further from medical centers. Our observed variations in case fatality ratio associated with health insurance and race/ethnicity may therefore be explained by the inequalities in access to quality health service.

In NYC, predominantly Asian neighborhoods contain large numbers of Chinese Americans and Korean Americans, diaspora [34] of countries that were first impacted by the COVID-19 pandemic in early 2020. It is plausible that this altered behaviors of some members of the community, potentially explaining the non-significant associations between the percentage of Asians within a neighborhood with the incidence rate of COVID-19, the death rate per capita, and the case fatality ratio in wave 1. In wave 2, neighborhoods with higher percentage of Asian population had a higher death rate per capita and case fatality ratio, but did not have an elevated COVID-19 incidence rate in wave 2. The lower incidence rate may be explained by higher adhereance to mask-wearing among Asian Americans [35]. The elevated death rate and case fatality ratio are consistent with reports showing that Asian Americans suffer disproportionately high COVID death rates and hospitalizations [36]. While Asians in NYC have insurance coverage that approaches 100%, some enclaves (such as Sunset Park) may have less access to high quality medical services [27].

Finally, both the death rate per capita and case fatality ratio were higher in neighborhoods with a higher percentage of older adults ($\geq$75 years) in both waves, and the impact on the case fatality ratio for neighborhoods with more older adults was even stronger in wave 2 than in wave 1. This is possibly explained by the rapid spread of disease in nursing homes with the more contagious variant of the virus in wave 2 [37, 38].

This study has several limitations. First, the COVID-19 outcomes data were obtained from NYC DOHMH COVID-19 Data on GitHub, a surveillance system set up for monitoring the public health crisis. Data quality were affected by incomplete testing, inconsistent reporting, and changing protocols. The data on the number of tests before June 9, 2020 were not available, so we cannot adjust for it in the models assessing risk factors associated with COVID-19 incidence and mortality rates. Moreover, there was a higher rate of test availability in wave 2 than in wave 1. These factors may have disproportionately affected some zip codes but not others. For example, research suggested that people of color may face increased barriers to testing [39], which may lead to an under-estimation of incidence rates of COVID-19 cases in neighborhoods with higher percentage of people of color [40]. Second, the neighborhood-level demographics and socioeconomic data were obtained from the Census Bureau based on the 2019 American Community Survey 5-year estimates, but the neighborhood characteristics may change with large outbound moves during the pandemic.

Conclusions

Spatial disparities in COVID-19 incidence and mortality across NYC neighborhoods were dynamic during the first two waves of outbreak. We find that neighborhoods with higher percentage of ethnic and racial minorities, older adult residents, large-size households, and low median household income had higher COVID-19 incidence and death rates in wave 1, but the associations with most neighborhood characteristics were attenuated in wave 2. Nevertheless, lower median household income was associated with higher rate of COVID-19 incidence and death rates in both waves and the association was slightly stronger in wave 2 even as the government provided additional economic support. Neighborhoods with higher percentage of Black and Asian populations had higher case fatality ratio in wave 2 even though the incidence rate did not increase, a factor that could be related to access to quality medical care. Our study raises a number of observations regarding the evolution of a pandemic in a major, dense, and diverse global city. It also points to a number of hypotheses that may be worthy of further exploration.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.annepidem.2022.04.008.

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