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Seroprevalence and demographic characteristics of SARS-CoV-2-infected residents of Kibera informal settlement during the COVID-19 pandemic in Nairobi, Kenya: a cross-sectional study

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ABSTRACT

Objectives To assess the prevalence of SARS-CoV-2 antibodies in the residents of Kibera informal settlement in Nairobi, Kenya, before vaccination became widespread, and explore demographic and health-related risk factors for infection.

Design A cross-sectional study.

Setting Kibera informal settlement, Nairobi, Kenya.

Participants Residents of Kibera informal settlement between October 2019 and August 2021, age 1 year and above who reported no current symptoms of COVID-19.

Main outcome measures Associations were determined between SARS-CoV-2 positive tests measured with one rapid test and two ELISAs and demographic and health-related factors, using Pearson's χ^2 test. Crude OR and adjusted OR were calculated to quantify the strength of associations between variables and seropositive status.

Results A total of 438 participants were recruited. Most (79.2%) were age 18–50 years; females (64.2%) exceeded males. More than one-third (39.1%) were unemployed; only 7.4% were in formal, full-time employment. Less than one-quarter (22.1%) self-reported any underlying health conditions. Nearly two-thirds (64.2%) reported symptoms compatible with COVID-19 in the previous 16 months; only one (0.23%) had been hospitalised with a reported negative COVID-19 test. 370 (84.5%) participants tested positive in any of the three tests. There was no significant difference in SARS-CoV-2 seropositivity across age, sex, presence of underlying health conditions, on medication or those ever tested for SARS-CoV-2. Multiple logistic regression analysis showed that COVID-19 symptoms in the previous 16 months were the only significant independent predictor of seropositivity (p=0.0085).

Conclusion High SARS-CoV-2 exposure with limited morbidity was found in the residents of Kibera informal settlement. The study confirms other reports of high SARS-CoV-2 exposure with limited morbidity in slum communities. Reasons cited include the high infectious disease burden on the African continent, demographic age structure and underreporting due to limited testing and lack of access to healthcare services; genetic factors may also play a role. These factors require further investigation.

STRENGTHS AND LIMITATIONS OF THIS STUDY

⇒ This was a community-based serosurveillance study where entry to households and data collection were facilitated by community health volunteers.
⇒ The study relied on self-reported demographic data, which are susceptible to recall bias.
⇒ The study collected a small volume of fingerpick blood which was more acceptable than venous blood and is convenient for serosurveillance studies in large populations.
⇒ Capillary blood collected into Microtainer EDTA tubes had to be transported to the testing site on the same day for testing and processing, so an accessible testing site is required.

INTRODUCTION

SARS-CoV-2, the cause of COVID-19, was first reported in Wuhan, Hubei Province, China, in November 2019 and rapidly spread across China and the world.[1] On 30 January 2020, the WHO declared the outbreak a Public Health Emergency of International Concern, and on 11 March 2020, the WHO Director General declared COVID-19 a pandemic.[2] Although the WHO declared the COVID-19 global health emergency over on 5 May 2023,[3] globally more than 777 million cases and more than 7 million deaths from COVID-19 had been reported by 5 January 2025, with more than 161 000 new cases and nearly 3000 deaths in the previous 28 days.[4] In the African region, more than 9.5 million confirmed cases and more than 175 000 deaths had been

reported cumulatively by 5 January 2025, although the numbers of cases and deaths reported in Africa are likely an underestimate due to low testing rates[5]; an assessment by the WHO Regional Office for Africa showed that only one in seven (14.2%) COVID-19 infections was being detected.[6] Studies from Kenya and other countries in Africa noted low mortality from COVID-19, despite high exposure rates.[7 8]

The modes of transmission of SARS-CoV-2 have been elucidated through detailed case contact studies. Respiratory transmission, with SARS-CoV-2 carried on tiny particles emitted from the respiratory tract, has been established as the clear and dominant route of spread; indirect transmission appears to be of limited importance despite initial concerns.[9] The clinical spectrum of COVID-19 varies from asymptomatic or presymptomatic infection, mild to moderate illness, to severe and critical illness characterised by respiratory failure and multiple organ dysfunction; varying proportions of infected persons remain asymptomatic.[10 11] Transmission from asymptomatic individuals is estimated to account for more than half of all transmissions.[12] Diagnostic testing using reverse transcriptase PCR (RT-PCR) based assays performed on respiratory specimens is the reference standard for establishing a microbiological diagnosis of COVID-19[13] but is constrained by the presence of virus to a few days before infection and a short time after infection. Seroepidemiological studies to detect host antibodies to SARS-CoV-2 are, therefore, important for estimating disease burden and providing a more complete picture of exposure to SARS-CoV-2 in a population.[14]

COVID-19 infection in Kenya

The first confirmed case of COVID-19 was reported in Kenya on 13 March 2020.[15] Restrictions to mitigate the spread of COVID-19 were instituted in March 2020 and were eased towards the end of 2020 until a second lockdown was instituted in five counties in March 2021; in May 2021, as the number of cases dropped, lockdown restrictions were again lifted.[16] COVID-19 vaccination was initiated in Kenya in March 2021, with vaccination numbers rising from August 2021 with increased vaccine availability. Kenya actively promoted vaccination through the COVID-19 Vaccination Acceleration Programme[17]; as of 16 May 2023, more than 18 million vaccine doses had been administered with 30.7% of the adult population (≥18 years) fully vaccinated. Kenya planned to vaccinate all adults and teenagers in 2022 and to provide third dose booster shots to all eligible adults.[18] On 11 March 2022, Kenya lifted all COVID-19 restrictions while urging continued personal public health measures; by June 2024, 344 000 cases and 5700 deaths had been reported since the pandemic started, rates that remained low in comparison with global figures.[4]

Seroprevalence data from Kenya targeting different population groups painted a concerning picture of the pandemic's progression across the country. Studies examining stored samples from blood donors in six regional blood transfusion centres, including the capital city Nairobi, revealed a dramatic rise in SARS-CoV-2 antibody prevalence over time. Seroprevalence increased from 4.3% (95% CI 2.9% to 5.8%) in samples collected between April and June 2020 to 48.5% (95% CI 45.2% to 52.1%) in samples taken just 1 year later from January to March 2021.[19 20] These samples were tested using a non-commercial validated ELISA for SARS-CoV-2 IgG against spike protein. The same assay was used to test stored blood from women attending antenatal care services at three hospitals in Kenya between August 2020 and October 2021: seroprevalence rose from 50% (95% CI 42% to 58%) in August 2020 to 85% (95% CI 78% to 92%) in October 2021 in Nairobi; 31% (95% CI 25% to 37%) in May 2021 to 71% (95% CI 64% to 77%) in October 2021 in Busia and from 1% (95% CI 0% to 3%) in September 2020 to 63% (95% CI 56% to 69%) in October 2021 in Kilifi.[21] Purposive testing of venous blood from healthcare workers between July and December 2020 using the same ELISA showed significant variation in overall seropositivity (20.8%: 17.5%–24.4%). Seroprevalence varied significantly (p<0.001) by site: 43.8% (35.8%–52.2%) in Nairobi, 12.6% (8.8%–17.1%) in Busia and 11.5% (7.2%–17.6%) in Kilifi; only 16 (2%) of the sampled healthcare workers reported acute respiratory symptoms at the time of sample collection.[22] Purposive testing of truck drivers and their assistants, using the same ELISA, conducted between September and October 2020 showed an overall seropositivity of 7.4%; none reported current or previous symptoms of illness.[23] Truck drivers and their assistants continued to transport essential supplies during the COVID-19 pandemic, placing them at increased risk of being infected and transmitting SARS-CoV-2 over a wide geographical area. In a study on samples collected from January to March 2020 from rural populations in western Kenya with and without HIV infection, 3.3% had detectable SARS-CoV-2 antibodies, with no difference between participants with and without HIV infection (3.1% vs 4.0%, p=0.68)[24]; this study used the Platelia SARS-CoV-2 Total Ab assay (Bio-Rad Laboratories, Hercules, California, USA). Participants denied symptoms except for one who reported a cough in the preceding week. In our study, SARS-CoV-2 seroprevalence in an informal settlement in Nairobi was conducted to supplement these data and determine exposure in a community subjected to overcrowding and lack of reliable clean water, housing, health services and waste management facilities, where preventive measures were difficult to apply. At the time of the study, Kenya was experiencing wave 4 of the pandemic predominated by the *Delta* variant of concern.[25]

Purpose of the study

This study assessed the prevalence of SARS-CoV-2 antibodies in the residents of Kibera informal settlement in Nairobi, Kenya, one of the sub-Sahara Africa's largest slums, before vaccination became widespread, and explored some of the major risk factors for infection. This study also provided an opportunity to determine

pathogen exposure in large numbers of persons in a pandemic situation using small blood volumes obtained from fingerprick samples.

MATERIALS AND METHODS

Study site

Kibera informal settlement stands on a 2.5-km^2 area of land located 5 km southwest of Nairobi's Central Business District. The population is estimated at 170 070, although this may be an underestimate.[26] Residents comprise the major ethnic communities in Kenya[27] with reportedly 116 women for every 100 men.[28] Kibera is governed by area chiefs as the local administrative arm of the government.

Study design

A cross-sectional study was performed to determine SARS-CoV-2 antibody prevalence in Kibera informal settlement, Nairobi, Kenya. The study was conducted between 2 and 13 August 2021 in 10 of the 14 Kibera villages, which provided a representation of the whole settlement. The Cochran sample size formula for larger populations was used to determine sample size.[29] Since the population of Kibera is above 170 000 and, approximately, 500 people had tested positive for SARS-CoV-2 at the time of the study, a sample size of 389 (~400) participants was determined, a target of 40 participants in each selected village (confidence level 99%; precision 0.01). In each village, every fifth household was selected; if a household declined participation, the next household was included. Entry to individual households was facilitated through community health volunteers who were formally assigned to these villages. Participants age 1 year and above who had been resident in Kibera since at least October 2019 were included.

Study methods

Five data collectors, each assigned to two villages, administered a brief questionnaire to each consenting participant, or their parent or legal guardian; data were collected directly into the Open Data Kit system installed in handheld tablets. The data were collected on the following: age, sex, length of residence in Kibera, pregnancy status (for women), main occupation and nature of employment, any underlying health conditions and type of condition, any medications and name of the medication, symptoms suggestive of COVID-19 in the previous 16 months (cough, fever, difficulty in breathing, shortness of breath and new loss of taste and smell), any hospitalisation and date (if known), ever tested for SARS-CoV-2, date and result (if known) and COVID-19 vaccination(s) and date (if known). Five laboratory staff accompanying the data collectors collected 500 µL of capillary blood from each participant by fingerprick into a Microtainer EDTA tube. Blood samples were transported to the Centre for Virus Research (CVR) laboratories for same-day testing on whole blood using the Standard Q COVID-19 IgM/IgG Combo rapid test (SD Biosensor Inc., Suwon, Gyeonggi, Republic of Korea). At the CVR laboratories, blood was separated the same day and plasma samples stored at -80 °C for further testing with two ELISAs: Wantai Total Ab (IgM/IgG/IgA) ELISA for SARS-CoV-2 (Wantai Biological Pharmacy Enterprise Co., Ltd., Beijing, China) and Platelia SARS-CoV-2 Total Ab (IgM/IgG/IgA) Assay (Bio-Rad Laboratories Inc., California, USA). The SARS-CoV-2 antibody tests selected in this survey were commercial tests approved for use in Kenya at the time of the study. Test performance is described in a separate paper.[30] Individuals with positive test results in any of the three tests were considered positive (for the ELISAs, optical density ≥1.0) and indeterminate ELISA results as negative (optical density 0.9–0.99). PCR or antigen testing was not performed for any of the study participants. Each participant was assigned a unique identification number; data files and blood sample labelling did not include participant names to ensure anonymity. Individuals who met the case definition of COVID-19 infection[31] at the time of recruitment were not included in the study and were referred to a nearby health facility for further investigation and management. The research teams followed government regulations for the prevention of COVID-19 transmission during data collection.[32]

Statistical analysis

Data were entered into Excel, cleaned and analysed using SAS version 9.4 (SAS Institute Inc.). Frequency and percentages were used to present the data; Pearson's χ^2 test was used to examine the association between seropositive results and various demographic and health-related factors, including age, sex, employment status, presence and types of underlying health conditions, on any type of medication, COVID-19 vaccination, previous symptoms compatible with COVID-19 and those ever tested for SARS-CoV-2. Simple logistic regression estimated the crude OR (COR) for each variable found to be significantly associated with seropositivity in the χ^2 test (≤0.20). Multiple logistic regression was used to calculate the adjusted OR (AOR), controlling for the effects of multiple variables simultaneously. The COR and AOR were calculated to quantify the strength of associations between the variables and seropositive status. Vaccinated individuals were included in the overall analysis as numbers were small (6.8%).

Patients and public involvement

This study was planned, designed and conducted as a shared activity with the Centre for Virus Research, Kenya Medical Research Institute. This included the development of the research protocol and study tools, training of data collectors and field laboratory staff and sample collection. The Centre for Virus Research staff conducted the laboratory tests. The study was discussed with the five area administrative chiefs, and entry to the households was facilitated through the community health volunteers assigned to the study villages. The study results will be presented to the Kibera chiefs, community health

volunteers and the participants through a community meeting.

RESULTS

Demographic data

A total of 438 participants consented to answer the questions and to a blood sample collection by fingerprick; one participant refused to divulge her occupation. Table 1 shows the information collected from the participant questionnaire.

Most participants (79.2%) were between age 18 and 50 years; only 4.8% were age ≤17 years and 16% were age ≥50 years. Females exceeded males across the 18–50 years age group by a ratio of 2:3, but males exceeded females in the <18 years and >50 years age groups. 11 female participants were pregnant; 2 were uncertain of their pregnancy status. Of the 419 participants age ≥16 years (the official age for employment in Kenya[33]), more than one-thirds (39.1%) were unemployed; the greatest number of unemployed participants were women in the 18–50 years age group (74.4% of unemployed participants). Less than one-quarter (22.1%) of participants self-reported any type of underlying health condition; the most common was cardiovascular disease, including hypertension (9.1% of all participants); only 14 (3.2%) participants reported underlying respiratory disease (including asthma). Underlying health conditions were most common in females in the 18–50 years age group (43.8% of all participants). Less than one-fifth (16%) of participants were taking one or more medications at the time of the survey; these included therapeutic drugs as well as vitamins and symptomatic treatment. 4 of the 18 participants with HIV infection reported not taking antiretroviral medication. Only 1 (0.23%) of the 281 (64.2%) participants reporting symptoms suggestive of COVID-19 in the previous 16 months had been hospitalised; he reported a negative SARS-CoV-2 test at that time. Only 19 (63%) of the 30 participants who reported receiving vaccination against SARS-CoV-2 had received two doses. Most participants could not recall the exact dates of vaccinations, but most received vaccinations between 1 April and 28 July 2021, within 4 months of the survey; one reported receiving vaccination in March 2021 and one in August 2021.

Serological results in relation to demographic data

The collection of an adequate volume of blood by fingerprick required lancets of sufficient depth (at least 1.8 mm; we used 2 mm); smaller lancets used initially did not produce an adequate flow of capillary blood for collection of the full 500 µL. Due to inadequate sample collection, there was insufficient sample in 72 participants to conduct the Platelia SARS-CoV-2 Total Ab Assay, the last test to be conducted. The comparison of performance between the three diagnostic tests (Wantai ELISA, Platelia ELISA and the rapid diagnostic test) is described in a separate paper.[30] In summary, the Wantai ELISA showed greater percentage positive results (82.6%) compared with the rapid test (51.8%) and the Platelia ELISA (69.7%); of the rapid test results, 23 were IgM positive, 151 were IgG positive and 53 were both IgM and IgG positive. Specificities of the rapid test and Platelia SARS-CoV-2 Total Ab Assay using the Wantai ELISA as the reference test were high (>90%). There was no significant difference in percentage positive results across participants' age, sex, presence of underlying health conditions, on any type of medication or those ever tested for SARS-CoV-2; there was a significant difference in percentage positive results according to participants' employment status (p=0.0176), COVID-19 symptoms in the previous 16 months (p=0.0099) and vaccination status (p=0.0561); this last variable was included in the multiple logistic regression analysis because of the p value of ≤0.20. The previously hospitalised participant tested negative with the rapid test but positive with the two ELISAs. Simple and multiple logistic regression analysis showed that having had COVID-19 symptoms in the previous 16 months was the only significant independent predictor of seropositivity in this population (p=0.0085) (table 2).

DISCUSSION

This study confirmed the expected high exposure to SARS-CoV-2 (84.5%) in residents of Kibera slum at the midpoint of the COVID-19 pandemic. Although nearly two-thirds of participants (62.4%) reported previous COVID-like symptoms, only one had been hospitalised and recovered. There was no significant association of SARS-CoV-2 infection with age, sex, underlying health conditions, being on any type of medication and having been previously tested for SARS-CoV-2; significant associations were found with employment status, COVID-19 vaccination and previous symptoms compatible with COVID-19, but multiple regression analysis showed an association only with previous symptoms suggestive of COVID-19. The categories <18 years of age and not applicable for employment status (<16 years) have wide CIs, indicating uncertainty about the true value of the OR; this may also be contributed to by the low participant numbers in these categories. In addition, the numbers of vaccinated participants were small. The high exposure in this population could be linked to the fact that a large proportion are casual labourers who walk up to 15 km daily in search of work and mix with populations in other areas; other groupings were also at risk due to the high population density in the Kibera slum resulting in high likelihood of transmission. The overall seroprevalence in our study is similar to that of women who attended antenatal care services in Nairobi (84.5% vs 85%) at a similar time frame (August 2021 vs October 2021),[21] which was conducted at the national referral hospital close to the Kibera slum. However, in our female population, seroprevalence was only 33.3% in the 18–30 years age group and 34.9% in the 31–50 years age group, implying that the population groups were different and suggesting the need for further investigation. The reasons for low rates of severe disease in this infected

Table 1 Seroprevalence of antibodies to SARS-CoV-2 by sociodemographic and other participant characteristics

Overall	n	Positive (%)	
	438	370 (84.5)	
Variables	n (%)	Positive(% (95% CI))	P (χ^2 test)
Age (years)			
≤17	21 (4.8)	14(3.2 (1.54 to 4.9))	0.0670
18–30	173 (39.5)	146(33.3 (28.9 to 37.8))	
31–50	174 (39.7)	153(34.9 (30.5 to 39.4))	
>50	70 (16)	57(13.0 (9.9 to 16.2))	
Sex			
Female	281 (64.2)	241(55.0 (50.3 to 59.7))	0.3185
Male	157 (35.8)	129(29.5 (25.2 to 33.7))	
Employment status (undisclosed was not included in the calculation of significance)			
Unemployed	164 (39.1)	137(31.4 (27.0 to 35.7))	0.0176
Self-employed	102 (24.3)	82(18.8 (15.1 to 22.4))	
Casual/part time	88 (21.0)	83(19.0 (15.3 to 22.7))	
Student	34 (8.1)	27(6.2 (3.9 to 8.4))	
Formal/regular	31 (7.4)	28(6.4 (4.1 to 8.7))	
Not applicable (<16 years)	18	12(2.7 (1.2 to 4.3))	
Undisclosed	1	1(0.23)	
Underlying health conditions			
No	341 (77.9)	287(65.5 (61.1 to 70.0))	0.7364
Yes	97 (22.1)	83(19.0 (15.3 to 22.6))	
Types of underlying health conditions	(% of all participants)		
Cardiovascular disease	40 (9.1)	32(7.3 (4.9 to 9.8))	0.4123
Stomach ulcer	25 (5.7)	20(4.6 (2.6 to 6.5))	0.5246
HIV	18 (4.1)	17(3.9 (2.1 to 5.7))	0.2330
Respiratory disease	14 (3.2)	12(2.7 (1.2 to 4.3))	0.8964
Diabetes	11 (2.5)	10(2.3 (0.9 to 3.7))	0.5506
On medication			
No	343 (78.3)	291(66.4 (62.0 to 70.9))	0.6888
Yes	95 (21.7)	79(18.0 (14.4 to 21.7))	
COVID-19 symptoms (previous 16 months)			
No	157 (35.8)	142(32.4 (28.0 to 36.8))	0.0099
Yes	281 (64.2)	228(52.1 (47.4 to 56.8))	
Ever tested for SARS-CoV-2			
No	371 (84.7)	311(71.0 (66.7 to 75.3))	0.3787
Yes	67 (15.3)	59 (10.3 to 16.7)	
Previous SARS-CoV-2 test			
Tested with negative result	54 (80.6)	48(71.6 (60.6 to 82.7))	*
Tested with positive result	4 (6.0)	4(6.0 (0.1 to 11.8))	
Tested with unknown result	9 (13.4)	7(10.4 (2.0 to 18.0))	
COVID-19 vaccination			
No	408 (93.2)	341(77.9 (74.0 to 81.8))	0.0561
Yes	30 (6.8)	29(6.6 (4.3 to 9.0))	

*No χ^2 possible due to a negative value in the tested negative category.

Table 2 Predictors of positivity to SARS-CoV-2 antibodies (n=437*)

Variables	Simple logistic regression analysis COR (95% CI)	P	Multiple logistic regression analysis AOR (95% CI)	P
Age (years)				
<18	0.4 (0.1 to 1.0)	0.0853	0.4 (0.0 to 5.0)	0.5574
18–30	1		1	
31–50	1.3 (0.7 to 2.5)		1.2 (0.6 to 2.3)	
>50	0.8 (0.4 to 1.7)		0.7 (0.3 to 1.6)	
Employment status				
Unemployed	1	0.0320	1	0.1739
Self-employed	0.8 (0.4 to 1.5)		0.9 (0.4 to 1.7)	
Casual/part time	3.3 (1.2 to 8.8)		3.2 (1.2 to 8.7)	
Student	0.8 (0.4 to 1.5)		0.8 (0.3 to 2.1)	
Formal/regular	1.8 (0.5 to 6.5)		1.8 (0.5 to 6.6)	
Not applicable (<16 years)	0.8 (0.3 to 1.9)		1.2 (0.1 to 19.9)	
COVID-19 symptoms (previous 16 months)				
No	1	0.0121	1	0.0085
Yes	0.5 (0.3 to 0.8)		0.4 (0.2 to 0.8)	
COVID-19 vaccination				
No	0.2 (0.0 to 1.3)	0.0893	0.2 (0.0 to 1.3)	0.0822
Yes	1		1	

*The one participant with undisclosed employment status was omitted.
AOR, adjusted OR; COR, crude OR.

population are unknown. The analysis of data from an ongoing population-based infectious disease surveillance platform showed that, in Kibera during the COVID-19 period observed (March 2020–December 2021), all-cause mortality was slightly lower with no significant change in mortality due to leading specific causes of death.[34]

Several explanations have been proposed for the overall low reported morbidity and mortality from COVID-19 in Africa despite high infection rates, including the high infectious disease burden on the African continent, demographic age structure[35–39] and underreporting due to limited testing and lack of access to healthcare services.[8] An integrative review concluded that low COVID-19 mortality and morbidity in Africa was largely a result of the combined effect of the younger African population and underreporting of COVID-19 cases,[40] although the protective effect of a younger population has been questioned.[8] In our study, the number of participants age >50 years was low (16%), which may also have contributed to the lower rate of severe disease in this population. Genetic factors may also explain the diversity observed in severity of COVID-19 in African populations due to single-nucleotide polymorphisms within the SARS-CoV-2 receptor genes; these have been demonstrated to have both detrimental and protective effects across ethnic groups.[41] Indeed, the population of Kibera represents a variety of the ethnic groups found in the eastern Africa region.

According to the UN, over 1 billion slum dwellers worldwide are mostly confined to three regions, one being sub-Saharan Africa.[42] For residents of urban slums, the difficulty in implementing COVID-19 preventive measures due to severe overcrowding was recognised early,[43 44] but the predicted high caseload and mortality rates from community transmission were not apparent, especially in Africa's slums.[45–47] This study supports seroprevalence studies in urban slums outside Africa that showed high exposure to the virus as well as low morbidity, with differing associated factors. Malani *et al* in a comparative study of slum and non-slum areas in Mumbai, India showed markedly higher proportions of positive tests in slum areas (54.1%) than in non-slum areas (16.1%), with lower infection fatality in slums (0.076%) than in non-slums (0.263%).[48] Nirala *et al* in a study across ten different slums in Patna, India found a seropositivity rate of 31.5% (95% CI 27.9 to 35.1) with seropositive status significantly associated with age 18–30 years, male gender, high-risk occupations (autorickshaw drivers, rickshaw pullers and street vendors), below poverty line economic status, residing in a hut or kutcha house (makeshift dwelling) and COVID-like symptoms in the preceding 1 month.[49] A study by Raqib *et al* comparing slum and non-slum areas in Bangladesh showed that seroprevalence was positively associated with limited years of formal education (AOR=1.61; 95% CI 1.43 to 1.82), lower income (AOR=1.23; 95% CI 1.03 to 1.46), overweight

(AOR=1.2835; 95% CI 1.26 to 1.97), diabetes (AOR=1.67; 95% CI 1.21 to 2.32) and heart disease (AOR=1.38; 95% CI 1.0 to1.86).[50] However, in a study by George *et al* in a large slum in South India with a reported overall COVID-19 seroprevalence of 57.9% (95% CI 53.4 to 62.3), age, education, occupation and presence of reported comorbidities were not significantly associated with seroprevalence.[51] The discrepancies between high seroprevalence, low morbidity and varying underlying factors suggest the need for further research to understand the potential protective factors and immune responses that may be at play in these informal settlements. The informal community in our study may have distinct characteristics that set it apart from other slum populations examined in previous research, including genetic variability. Factors such as community resilience, social support networks and environmental conditions may vary from place to place and could play a role in mitigating the impact of COVID-19 and influencing the observed lack of associations with reported risk factors.

Comorbidities associated with severe COVID-19 have also been examined in other populations. Fatmawati and Mulyanti reviewed nine studies from Asia and Europe that showed risk factors for severe COVID-19 included age, gender, chronic comorbidities, cardiovascular disease, diabetes, hypertension, kidney failure, cancer and a history of smoking.[52] Wang *et al* using self-reported data from a survey of adults in the USA reported that individuals with underlying health conditions were more likely to become infected with SARS-CoV-2 and have more severe postinfection symptoms.[53] Kompaniyets *et al* in a cross-sectional study of children age ≤18 years in the USA reported that underlying health conditions, such as type 1 diabetes, cardiac and circulatory congenital anomalies and obesity, were more associated with severe COVID-19 or death.[54] Costa *et al* in a review of published data up to June 2020 reported that patients with metabolic disorders, including obesity, diabetes, cardiovascular disease and liver disease, faced a higher risk of SARS-CoV-2 infection and were associated with a significantly worse outcome.[55] Wu *et al* in a review of published papers up to April 2020 reported that diabetes increased the mortality of patients with COVID-19.[56] However, the findings from our study challenge the assumptions that COVID-19 risk factors are necessarily linked to the severity of disease. Males have also been reported to be at higher risk of severe illness and increased mortality than females[12 57]; this was also not evident in our study.

Our study also explored the use of small blood volume samples collected through fingerprick. We found fingerprick sampling a convenient and acceptable way of conducting a serosurvey across a large population that included small children and for evaluating new technologies. Testing kits used for serosurveys should, therefore, ideally use whole blood or plasma separated from capillary blood. Our study used three tests concurrently to detect antibodies to SARS-CoV-2: one rapid test and two ELISA tests. Since the start of the COVID-19 pandemic, molecular testing for SARS-CoV-2 virus using RT-PCR-based assays performed on respiratory specimens has been central to disease management and control.[14] Tests for SARS-CoV-2 antigens on clinical specimens using immunoassays and rapid tests have also been used but are limited by suboptimal sensitivity.[58 59] Molecular and antigen tests are constrained by detection of virus to a few days before infection and a short time after infection. In a systematic review of longitudinal studies of RT-PCR test results in symptomatic SARS-CoV-2 infections, the highest percentage of virus detection in nasopharyngeal swabs by PCR was 89% between 0 and 4 days postsymptom onset, dropping to 54% (95% CI 47 to 61) after 10–14 days.[60] Tests for detecting antibodies to SARS-CoV-2 applicable outside research laboratory settings include rapid tests using lateral flow immunology and ELISA tests. In a study by Guo *et al* using an ELISA based on recombinant viral nucleocapsid protein, the median time to IgM and IgA antibody detection after symptom onset was 5 (IQR 3–6) days, while IgG was detected at 14 (IQR 10–18) days.[61] Zhao *et al*, using an ELISA prepared from recombinant antigen containing the receptor binding domain of SARS-CoV-2 spike protein, reported that median times from symptom onset to total antibody, IgM and IgG seroconversion were 11, 12 and 14 days, respectively[62]; the presence of antibodies was <40% among patients within 1 week of onset and rapidly increased to 100% (total antibody—94.3% (IgM) and 79.8% (IgG)) by day 15 after onset; there were also negative antibody findings in 7% patients, possibly due to blood samples not taken at an appropriate time after symptom onset. In a report by Qu *et al* using an IgG/IgM chemiluminescent immunoassay with combined nucleocapsid protein and spike glycoprotein antigens, seroconversion time of IgG antibody was earlier than IgM antibody: 97.6% of patients (40/41) were positive with IgG and 87.8% (36/41) with IgM, with a median time of seroconversion for IgG at 11 days (8–16 days) and for IgM at 14 days (8–28 days) after disease onset. The level of IgG antibody reached the highest concentration on day 30, while the highest concentration of IgM antibody appeared on day 18 but then began to decline.[63] Hoffman *et al* found no statistical difference between testing samples taken from PCR-confirmed COVID-19 cases between 9 and 17 days and 18 and 29 days for either IgM or IgG seropositivity.[64] Generally, IgM is produced first with a later switch towards IgG production, but studies on SARS-associated coronaviruses suggest that IgM and IgG often develop at around the same time.[65 66] In general, the detection of antibodies is better in samples taken >14 days after onset of disease due to the time taken for antibody development.[67 68] Reported duration of antibody after natural confirmed infection is variable, including >6 months,[69] up to 20 months in unvaccinated adults in the USA after confirmed COVID-19 infection,[70] and more than 2 years in patients in Wuhan, China.[71] It is, therefore, probable that most natural infections occurring within the previous 16 months in our study population were

detected, although the relevance of the IgM and IgG antibody findings is unclear.

Serological studies that assess prior infection and immunity to infectious diseases are essential for epidemiological studies, ongoing surveillance, vaccine studies and potentially for risk assessments of healthcare workers, and provide an indication of previous as well as recent exposure in a population. Surveillance, therefore, remains fundamental to understanding the evolution of SARS-CoV-2 infection, the risk factors for severe disease and the impact of vaccination and public health and social measures.[72] Although hospital admissions and severe outcomes from COVID-19 have substantially decreased since the start of the pandemic, COVID-19-related deaths remain substantial: in the USA, COVID-19 still ranks as the tenth most common cause of death. The percentage of positive tests for SARS-CoV-2, a key indicator of community spread, reached peak levels of 12.9% in January 2024.[73] Since disease mitigation measures implemented in many countries severely affected the global economy and financial markets,[74] and substantially impacted the inadequately prepared health systems in Africa,[75] health systems need to be vigilant of emerging SARS-CoV-2 variants and the possibility of new surges in cases and deaths. As WHO recommends countries transition from emergency mode to managing COVID-19 alongside other infectious diseases, providing a more complete picture of the total number of people infected with SARS-CoV-2 remains an important measure for guiding public health responses.[76] The recent establishment of a global network to detect and monitor novel coronaviruses of public health importance will facilitate early detection, risk assessment and response to coronavirus-related health challenges.[77] Well-designed surveillance systems remain core to monitoring acute viral respiratory infections to inform public health measures, health system capacities, impact of vaccination programmes and other control measures.[78]

Conclusions

This study reports high SARS-CoV-2 exposure in a slum community in Nairobi, Kenya, with limited morbidity; only recent COVID-19 symptoms were a significant independent predictor of seropositivity. This study confirms other reports of high SARS-CoV-2 exposure with limited morbidity in slum communities. The study also supports the convenient use of small blood volumes for conducting population serosurveys. Use of serological assays to conduct seroprevalence studies will continue to remain important as more robust tests are developed, especially point of care tests. Public health systems would greatly benefit from serosurveillance to supplement and strengthen the existing COVID-19 and other case-based infectious disease surveillance strategies.[79]

Study limitations

This study was conducted during the working week during working hours, which may explain the low number of male participants of working age and low number of those formally employed. The tests used were limited by the availability of approved tests at the time.

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REFERENCES

1 Zhu H, Wei L, Niu P. The novel coronavirus outbreak in Wuhan, China. *Glob Health Res Policy* 2020;5:6.
2 Cucinotta D, Vanelli M. WHO Declares COVID-19 a Pandemic. *Acta Biomed* 2020;91:157–60.

3 World Health Organization. WHO Director-General's opening remarks at the media briefing, 2023. Available: https://www.who.int/news-room/speeches/item/who-director-general-s-opening-remarks-at-the-media-briefing---5-may-2023
4 World Health Organization. Health Emergencies Programme, Available: https://data.who.int/dashboards/covid19/cases?n=c
5 Mwananyanda L, Gill CJ, MacLeod W, *et al*. Covid-19 deaths in Africa: prospective systematic postmortem surveillance study. *BMJ* 2021;372:n334.
6 World Health Organization Regional Office for Africa. Six in seven COVID-19 infections go undetected in Africa, 2021. Available: https://www.afro.who.int/news/six-seven-covid-19-infections-go-undetected-africa
7 Ngere I, Dawa J, Hunsperger E, *et al*. High seroprevalence of SARS-CoV-2 but low infection fatality ratio eight months after introduction in Nairobi, Kenya. *Int J Infect Dis* 2021;112:25–34.
8 McKay T, Robinson RS, Musungu S, *et al*. The Missing Millions: Uncovering the Burden of Covid-19 Cases and Deaths in the African Region. *Population & Development Rev* 2024;50:7–58.
9 Meyerowitz EA, Richterman A, Gandhi RT, *et al*. Transmission of SARS-CoV-2: A Review of Viral, Host, and Environmental Factors. *Ann Intern Med* 2021;174:69–79.
10 Nishiura H, Kobayashi T, Miyama T, *et al*. Estimation of the asymptomatic ratio of novel coronavirus infections (COVID-19). *Int J Infect Dis* 2020;94:154–5.
11 Ogalo EA, Gudu E, Andale T, *et al*. Clinical spectrum of COVID-19 at a national referral hospital in western Kenya during the period 2020–2021. *Front Virol* 2023;3:1202742.
12 Johansson MA, Quandelacy TM, Kada S, *et al*. SARS-CoV-2 Transmission From People Without COVID-19 Symptoms. *JAMA Netw Open* 2021;4:e2035057.
13 Oliveira MC, Scharan KO, Thomés BI, *et al*. Diagnostic accuracy of a set of clinical and radiological criteria for screening of COVID-19 using RT-PCR as the reference standard. *BMC Pulm Med* 2023;23:81.
14 Cheng MP, Yansouni CP, Basta NE, *et al*. Serodiagnostics for Severe Acute Respiratory Syndrome-Related Coronavirus 2: A Narrative Review. *Ann Intern Med* 2020;173:450–60.
15 Aluga MA. Coronavirus Disease 2019 (COVID-19) in Kenya: Preparedness, response and transmissibility. *J Microbiol Immunol Infect* 2020;53:671–3.
16 World Bank. Socioeconomic impacts of COVID-19 in Kenya, 2021. Available: https://documents1.worldbank.org/curated/en/949721626096781344/pdf/Socioeconomic-Impacts-of-COVID-19-in-Kenya.pdf
17 Ministry of Health, Republic of Kenya. National COVID-19 Vaccine Deployment Plan. 2021.
18 Republic of Kenya. Kenya COVID-19 Vaccination Program: Daily Situation Report. 2022.
19 Uyoga S, Adetifa IMO, Karanja HK, *et al*. Seroprevalence of anti-SARS-CoV-2 IgG antibodies in Kenyan blood donors. *Science* 2021;371:79–82.
20 Uyoga S, Adetifa IMO, Otiende M, *et al*. Prevalence of SARS-CoV-2 Antibodies From a National Serosurveillance of Kenyan Blood Donors, January-March 2021. *JAMA* 2021;326:1436–8.
21 Lucinde RK, Mugo D, Bottomley C, *et al*. Sero-surveillance for IgG to SARS-CoV-2 at antenatal care clinics in three Kenyan referral hospitals: Repeated cross-sectional surveys 2020-21. *PLoS One* 2022;17:e0265478.
22 Etyang AO, Lucinde R, Karanja H, *et al*. Seroprevalence of Antibodies to Severe Acute Respiratory Syndrome Coronavirus 2 Among Healthcare Workers in Kenya. *Clin Infect Dis* 2022;74:288–93.
23 Kagucia EW, Gitonga JN, Kalu C, *et al*. Seroprevalence of anti-sars-cov-2 igg antibodies among truck drivers and assistants in kenya. *Epidemiology* [Preprint] 2021.
24 Crowell TA, Daud II, Maswai J. SARS-CoV-2 antibody prevalence in people with and without HIV in rural western Kenya. *AIDS* 2021;35:2401–4.
25 Nasimiyu C, Matoke-Muhia D, Rono GK, *et al*. Imported SARS-CoV-2 Variants of Concern Drove Spread of Infections across Kenya during the Second Year of the Pandemic. *COVID* 2022;2:586–98.
26 Kenya National Bureau of Statistics. The 2009 Kenya Population and Housing Census. 2010.
27 Mutisya E, Yarime M. Understanding the grassroots dynamics of slums in Nairobi: the dilemma of Kibera informal settlements. *Int Transact J Eng Manage Appl Sci Technol* 2011;2. Available: http://tuengr.com/V02/197-213.pdf
28 UN Habitat. COVID-19 exposes the harsh realities of gender inequality in slums, 2020. Available: https://unhabitat.org/news/03-jun-2020/covid-19-exposes-the-harsh-realities-of-gender-inequality-inslums#:~:text=In%20Kibera%2C%20Kenya%2C%20the%20world's,women%20for
29 Statistics How To. Sample size in Statistics (how to find it): Excel, Cochran's formula, general tips, Available: https://www.statisticshowto.com/probability-and-statistics/find-sample-size/
30 Carter JY, Khamadi S, Mwangi J, *et al*. Performance of one rapid test and two ELISAs for a SARS-CoV-2 seroprevalence survey in Kibera informal settlement. [Manuscript submitted for publication].
31 World Health Organization. COVID-19: Case definitions. 2020.
32 Ministry of Health, Kenya. *Interim guidelines on management of COVID-19 in Kenya. COVID-19, Infection Prevention and Control (IPC) and case management*. 2020.
33 Laws of Kenya. Employment Act. Chapter 226. Revised Edition 2012. 2007.
34 Oduor C, Audi A, Kiplangat S, *et al*. Estimating excess mortality during the COVID-19 pandemic from a population-based infectious disease surveillance in two diverse populations in Kenya, March 2020-December 2021. *PLOS Glob Public Health* 2023;3:e0002141.
35 Wamai RG, Hirsch JL, Van Damme W, *et al*. What Could Explain the Lower COVID-19 Burden in Africa despite Considerable Circulation of the SARS-CoV-2 Virus? *Int J Environ Res Public Health* 2021;18:8638.
36 Musa HH, Musa TH, Musa IH, *et al*. Addressing Africa's pandemic puzzle: Perspectives on COVID-19 transmission and mortality in sub-Saharan Africa. *Int J Infect Dis* 2021;102:483–8.
37 Adams J, MacKenzie MJ, Amegah AK, *et al*. The Conundrum of Low COVID-19 Mortality Burden in sub-Saharan Africa: Myth or Reality? *Glob Health Sci Pract* 2021;9:433–43.
38 Tessema SK, Nkengasong JN. Understanding COVID-19 in Africa. *Nat Rev Immunol* 2021;21:469–70.
39 Kusi KA, Frimpong A, Partey FD, *et al*. High infectious disease burden as a basis for the observed high frequency of asymptomatic SARS-CoV-2 infections in sub-Saharan Africa. *AAS Open Res* 2021;4:2.
40 Manna OK, Costa Clemens SA, Clemens R. Investigating the Possible Reasons for the Low Reported Morbidity and Mortality of COVID-19 in African Countries: An Integrative Review. *Pediatr Infect Dis J* 2023;42:e222–8.
41 Adimulam T, Arumugam T, Gokul A, *et al*. Genetic Variants within SARS-CoV-2 Human Receptor Genes May Contribute to Variable Disease Outcomes in Different Ethnicities. *Int J Mol Sci* 2023;24:8711.
42 United Nations. New York: United Nations Publication. [2020-04-23]. Urbanization and development: emerging futures. World Cities report, 2016. Available: https://tinyurl.com/y4eknchmh
43 Gibson L, Rush D. Novel Coronavirus in Cape Town Informal Settlements: Feasibility of Using Informal Dwelling Outlines to Identify High Risk Areas for COVID-19 Transmission From A Social Distancing Perspective. *JMIR Public Health Surveill* 2020;6:e18844.
44 Wasdani KP, Prasad A. The impossibility of social distancing among the urban poor: the case of an Indian slum in the times of COVID-19. *Local Environ* 2020;25:414–8.
45 UN Habitat. Coronavirus will travel "incredibly fast" in Africa's slums, 2020. Available: https://unhabitat.org/coronavirus-will-travel-incredibly-fast-in-africas-slums-un-habitat-chief-warns
46 Arora RK, Joseph A, Wyk J, *et al*. SeroTracker: a global SARS-CoV-2 seroprevalence dashboard. *Lancet Infect Dis* 2021;E75–76.
47 Ilesanmi OS, Oderinde TM, Afolabi AA. The urban slums: Potential source of COVID-19 spikes in Africa. *Public Health in Practice* 2020;1:100052.
48 Malani A, Shah D, Kang G, *et al*. Seroprevalence of SARS-CoV-2 in slums versus non-slums in Mumbai, India. *Lancet Glob Health* 2021;9:e110–1.
49 Nirala SK, Naik BN, Chaudhary N, *et al*. Sero-epidemiological survey of SARS-Cov2 in urban slums of a capital city: A cross- sectional study. *J Family Med Prim Care* 2022;11:2709–16.
50 Raqib R, Sarker P, Akhtar E, *et al*. Seroprevalence of SARS-CoV-2 infection and associated factors among Bangladeshi slum and non-slum dwellers in pre-COVID-19 vaccination era: October 2020 to February 2021. *PLoS One* 2022;17:e0268093.
51 George CE, Inbaraj LR, Chandrasingh S, *et al*. High seroprevalence of COVID-19 infection in a large slum in South India; what does it tell us about managing a pandemic and beyond? *Epidemiol Infect* 2021;149:1–6.
52 Fatmawati F, Mulyanti S, Martono. Risk Factors Associated with the Severity of COVID-19. *Malays J Med Sci* 2023;30:84–92.
53 Wang B, Yuan S, Ruan S, *et al*. Associations between underlying diseases with COVID-19 and its symptoms among adults: a cross-sectional study. *Front Public Health* 2023;11:1210800.

54 Kompaniyets L, Agathis NT, Nelson JM, *et al*. Underlying Medical Conditions Associated With Severe COVID-19 Illness Among Children. *JAMA Netw Open* 2021;4:e2111182.
55 Costa FF, Rosário WR, Ribeiro Farias AC, *et al*. Metabolic syndrome and COVID-19: An update on the associated comorbidities and proposed therapies. *Diabetes Metab Syndr* 2020;14:809–14.
56 Wu Z, Tang Y, Cheng Q. Diabetes increases the mortality of patients with COVID-19: a meta-analysis. *Acta Diabetol* 2021;58:139–44.
57 Jin J-M, Bai P, He W, *et al*. Gender Differences in Patients With COVID-19: Focus on Severity and Mortality. *Front Public Health* 2020;8:152.
58 Adnan N, Khandker SS, Haq A, *et al*. Detection of SARS-CoV-2 by antigen ELISA test is highly swayed by viral load and sample storage condition. *Expert Rev Anti Infect Ther* 2022;20:473–81.
59 Høeg TB, Prasad V. Rapid antigen testing for COVID-19: Decreasing diagnostic reliability, potential detrimental effects and a lack of evidence to support continued public funding of community-based testing. *Public Health Pract (Oxf)* 2023;6:100451.
60 Mallett S, Allen AJ, Graziadio S, *et al*. At what times during infection is SARS-CoV-2 detectable and no longer detectable using RT-PCR-based tests? A systematic review of individual participant data. *BMC Med* 2020;18:346.
61 Guo L, Ren L, Yang S, *et al*. Profiling Early Humoral Response to Diagnose Novel Coronavirus Disease (COVID-19). *Clin Infect Dis* 2020;71:778–85.
62 Zhao J, Yuan Q, Wang H, *et al*. Antibody Responses to SARS-CoV-2 in Patients With Novel Coronavirus Disease 2019. *Clin Infect Dis* 2020;71:2027–34.
63 Qu J, Wu C, Li X, *et al*. Profile of Immunoglobulin G and IgM Antibodies Against Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2). *Clin Infect Dis* 2020;71:2255–8.
64 Hoffman T, Nissen K, Krambrich J, *et al*. Evaluation of a COVID-19 IgM and IgG rapid test; an efficient tool for assessment of past exposure to SARS-CoV-2. *Infect Ecol Epidemiol* 2020;10:1754538.
65 Hsueh P-R, Huang L-M, Chen P-J, *et al*. Chronological evolution of IgM, IgA, IgG and neutralisation antibodies after infection with SARS-associated coronavirus. *Clin Microbiol Infect* 2004;10:1062–6.
66 Li G, Chen X, Xu A. Profile of specific antibodies to the SARS-associated coronavirus. *N Engl J Med* 2003;349:508–9.
67 Hanssen DAT, Slaats M, Mulder M, *et al*. Evaluation of 18 commercial serological assays for the detection of antibodies against SARS-CoV-2 in paired serum samples. *Eur J Clin Microbiol Infect Dis* 2021;40:1695–703.
68 Gong F, Wei H, Li Q, *et al*. Evaluation and comparison of serological methods of COID-19 diagnosis. *Front Mol Biosci* 2021.
69 Dan JM, Mateus J, Kato Y, *et al*. Immunological memory to SARS-CoV-2 assessed for up to 8 months after infection. *Science* 2021;371:eabf4063.
70 Alejo JL, Mitchell J, Chang A, *et al*. Prevalence and Durability of SARS-CoV-2 Antibodies Among Unvaccinated US Adults by History of COVID-19. *JAMA* 2022;327:1085–7.
71 Guo L, Zhang Q, Gu X, *et al*. Durability and cross-reactive immune memory to SARS-CoV-2 in individuals 2 years after recovery from COVID-19: a longitudinal cohort study. *Lancet Microbe* 2024;5:e24–33.
72 Wold Health Organization. Update to requirements for reporting COVID-19 surveillance data under the International Health Regulations (IHR 2005): Addendum to Public health surveillance for COVID-19 interim guidance, 2023. Available: https://www.who.int/publications/i/item/WHO-2019-nCoV-Surveillance-Guidance-Addendum-2023-1
73 National Centre for Immunization and Respiratory Diseases. The changing threat of COVID-19, 2024. Available: https://www.cdc.gov/ncird/whats-new/changing-threat-covid-19.html
74 Pak A, Adegboye OA, Adekunle AI, *et al*. Economic Consequences of the COVID-19 Outbreak: the Need for Epidemic Preparedness. *Front Public Health* 2020;8:241.
75 Tessema GA, Kinfu Y, Dachew BA, *et al*. The COVID-19 pandemic and healthcare systems in Africa: a scoping review of preparedness, impact and response. *BMJ Glob Health* 2021;6:e007179.
76 World Health Organization. Media Briefing, 2023. Available: https://www.who.int/director-general/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing---5-may-2023
77 World Health Organization. WHO launches CoViNet: a global network for coronaviruses, 2024. Available: https://www.who.int/news/item/27-03-2024-who-launches-covinet--a-global-network-for-coronaviruses
78 European Centre for Disease Prevention and Control. Factsheet for health professionals on COVID-19, Available: https://www.ecdc.europa.eu/en/infectious-disease-topics/z-disease-list/covid-19/facts/surveillance-covid-19
79 Haselbeck AH, Im J, Prifti K, *et al*. Serology as a Tool to Assess Infectious Disease Landscapes and Guide Public Health Policy. *Pathogens* 2022;11:732.