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SARS-CoV-2 seroprevalence among the general population and healthcare workers in India, December 2020–January 2021

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ABSTRACT

Background: Earlier serosurveys in India revealed seroprevalence of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) of 0.73% in May–June 2020 and 7.1% in August–September 2020. A third serosurvey was conducted between December 2020 and January 2021 to estimate the seroprevalence of SARS-CoV-2 infection among the general population and healthcare workers (HCWs) in India.
Methods: The third serosurvey was conducted in the same 70 districts as the first and second serosurveys. For each district, at least 400 individuals aged ≥10 years from the general population and 100 HCWs from subdistrict-level health facilities were enrolled. Serum samples from the general population were tested for the presence of immunoglobulin G (IgG) antibodies against the nucleocapsid (N) and spike (S1-RBD) proteins of SARS-CoV-2, whereas serum samples from HCWs were tested for anti-S1-RBD. Weighted seroprevalence adjusted for assay characteristics was estimated.
Results: Of the 28,598 serum samples from the general population, 4585 (16%) had IgG antibodies against the N protein, 6647 (23.2%) had IgG antibodies against the S1-RBD protein, and 7436 (26%) had IgG antibodies against either the N protein or the S1-RBD protein. Weighted and assay-characteristic-adjusted seroprevalence against either of the antibodies was 24.1% [95% confidence interval (CI) 23.0–25.3%]. Among 7385 HCWs, the seroprevalence of anti-S1-RBD IgG antibodies was 25.6% (95% CI 23.5–27.8%).
Conclusions: Nearly one in four individuals aged ≥10 years from the general population as well as HCWs in India had been exposed to SARS-CoV-2 by December 2020.

Introduction

Population-based serosurveys are recommended to estimate the proportion of a population already infected with severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2). Repeated cross-sectional serosurveys conducted in the same geographical location provide estimates to monitor trends over a period of time (World Health Organization, 2020a). Information from repeated cross-sectional surveys is valuable for public health decision makers to design and revise containment strategies. A meta-analysis undertaken by Chen et al. (2021) estimated that the overall global seroprevalence of SARS-CoV-2 was 8.0% in the general population and 17.1% among healthcare workers (HCWs).

With more than 10 million laboratory-confirmed cases and nearly 150,000 reported deaths as of 31 December 2020, India has the second highest reported number of cases of coronavirus disease 2019 (COVID-19) globally (World Health Organization, 2020b). The nationwide lockdown imposed between March and May 2020 in India was relaxed in a phased manner from June 2020, allowing interstate and interdistrict movement of people as well as restoration of economic activities (Ministry of Home Affairs, Government of India, 2020, 2021). Two population-based serial serosurveys conducted in 70 Indian districts indicated that the prevalence of SARS-CoV-2 infection among adults had increased 10-fold, from 0.73% [95% confidence interval (CI) 0.34–1.13%] in May–June 2020 to 7.1% (95% CI 6.2–8.2%) in August–September 2020 (Murhekar et al., 2020, 2021). The number of infections per reported COVID-19 case decreased from 81.6–130.1 in May–June 2020 to 26–32 in August–September 2020, mainly due to improvements in testing capacity and the number of tests performed in the country (Murhekar et al., 2020, 2021).

SARS-CoV-2 poses a high occupational risk to HCWs, who are at the forefront of management of COVID-19 cases in hospital settings. Knowledge of the burden of infection among HCWs is important to gauge the risk of within and outside hospital transmission of SARS-CoV-2, and evaluate in-hospital infection control practices and adherence to non-pharmaceutical interventions (Piccoli et al., 2021).

The number of cases of COVID-19 in India has shown a downward trend since mid-September 2020, with the reported number of cases declining from more than 90,000 per day in September 2020 to less than 20,000 cases per day in December 2020. This declining trend has been seen in all Indian states, except Kerala (FETP Network – Chennai, India, 2021). In this context, the authors conducted a third nationwide serosurvey between December 2020 and January 2021 to estimate the seroprevalence of SARS-CoV-2 antibodies in the general population, and determine the trends in infection since the previous serosurveys. In

addition, seroprevalence was estimated among HCWs working in subdistrict-level public health facilities.

Methods

Survey of general population

The third serosurvey followed the same methodology as the first and second nationwide serosurveys (Murhekar et al., 2020, 2021) (see online Supplementary material). Briefly, the third population-based serosurvey was conducted in the same 700 clusters (villages in rural areas and wards in urban areas) from 70 districts selected at random across India as in the first two serosurveys. The authors aimed to select a minimum of 400 individuals aged ≥10 years from each district, with a total sample size of 28,000 individuals (see online Supplementary material). The survey teams first selected four random locations from each cluster. Starting from a random household in each location, contiguous households were visited. All household members aged ≥10 years who were permanent residents in the area were enumerated, and consenting individuals present at the time of the visit of the survey team were included in the survey. No additional visits were made to include households which were locked or household members who were not present at the time of the first visit. In order to select at least 40 individuals from each cluster, the field teams visited a minimum of four households from each of the four random points, and enrolled at least 10 individuals per random starting location. If the teams did not identify 10 eligible individuals from the four households, more households were visited. The survey was conducted between 18 December 2020 and 6 January 2021.

Survey of HCWs

Two to three subdistrict-level public health facilities (e.g., 'taluk' or subdivisional hospital, community or primary health centre) closest to the selected cluster/s for the household survey were selected from each of the 70 districts identified for the general population survey. All consenting individuals working in these facilities were included to ensure participation of ≥100 HCWs from each district.

Data collection

Eligible individuals from the general population and HCWs who consented to participate were interviewed using the Open Data Kit mobile application (https://opendatakit.org/) to collect information on sociodemographic details, history of symptoms suggestive of COVID-19 since March 2020 (e.g., fever, cough, shortness of breath, sore throat, new loss of taste or smell, fatigue), contact with laboratory-confirmed COVID-19 cases, and history of COVID-19 illness. Venous blood (3–5 mL) was collected from each participant, and centrifuged serum samples were transported to ICMR National Institute of Epidemiology, Chennai under cold chain conditions.

Laboratory investigations

Serum samples collected from individuals from the general population were tested for the presence of immunoglobulin G (IgG) antibodies against SARS-CoV-2 on the Advia Centaur Immunoassay system using the Siemens SARS-CoV-2 IgG assay (Siemens Healthineers, India, Mumbai) and Abbott Architect i2000SR automated analyser using the Abbott SARS-CoV-2 IgG assay (Abbott Park, IL, USA). The Siemens assay detects IgG antibodies against the spike protein of the receptor binding domain (S1-RBD), and the Abbott assay detects IgG antibodies against the nucleocapsid (N) protein of SARS-CoV-2. Serum samples from HCWs were tested only for IgG antibodies against the S1-RBD protein. Sensitivity and specificity of the Siemens IgG assay are 100% and 99.90% respectively, compared with 100% and 99.6% for the Abbott IgG assay (Center for Devices and Radiological Health, 2021). Serum samples with cut-off indices (COI) ≥1.0 on the Siemens IgG assay or ≥1.4 on the Abbott IgG assay were considered as positive for IgG antibodies against SARS-CoV-2. One hundred and fifty positive serum samples and 150 negative serum samples for each assay were retested for quality control purposes.

Statistical analysis

The characteristics of study participants are described as percentage, mean and standard deviation (SD). The reported occupations were categorized as high risk and low risk on the basis of the potential risk of exposure to a known or unknown COVID-19 case. For example, occupations such as HCWs, police or security personnel, shopkeepers, bus or taxi drivers, and bank employees were considered as high-risk occupations; and farmers, retired employees, students, information technology professionals and homemakers were considered as low-risk occupations (Murhekar et al., 2021). The weighted seroprevalence of IgG antibodies against the N protein and the S1-RBD protein were estimated separately, along with 95% CI, using a random-effects model to account for cluster sampling. Sampling weights were calculated as the product of the inverse of the sampling fraction for the selection of districts and the selection of villages or wards from each district. Weighted seroprevalence was further adjusted for the sensitivity and specificity of the respective assays (Sempos and Tian, 2021). Overall seroprevalence in the general population was estimated by considering serum samples positive on any of the assays. Weighted overall seroprevalence was adjusted for joint sensitivity and specificity of the two assays (Sempos and Tian, 2021). Seroprevalence among HCWs was considered on the basis of the anti-S1 assay alone. In addition, overall seroprevalence was calculated by age group, sex, area of residence and COVID-19-related characteristics of the study participants.

The first serosurvey was conducted among adults alone, whereas individuals aged ≥10 years were surveyed in the second and third surveys. The serum samples in the second serosurvey were tested only for IgG antibodies against the N protein using the Abbott assay. For comparison of seroprevalence in the three surveys, one adult per household was selected at random from the survey database, and adjusted seroprevalence of IgG antibodies against the N protein was estimated among these adults.

Overall adjusted seroprevalence in the general population aged ≥10 years was applied to the total population of the entire country aged ≥10 years to estimate the total number of cases of SARS-CoV-2 infection. Studies indicate that IgG antibodies start appearing between 7 and 14 days after symptom onset and reverse transcriptase polymerase chain reaction (RT-PCR) positivity (Long et al., 2020). The infection to case ratio was estimated by dividing the estimated number of SARS-CoV-2 infections by the number of reported COVID-19 cases detected by RT-PCR or rapid antigen test 1 week (19 December 2020) and 2 weeks (12 December 2020) before the median survey date (26 December 2020).

Sensitivity analysis

IgG antibodies against SARS-CoV-2 infection decline over time (Ripperger et al., 2020; Bolotin et al., 2021). The COI for different assays specified by manufacturers are based on ≥14 days convalescent sera. Lowering the COIs could improve the sensitivity of the assays used for population-based serosurveys (Bolotin et al.,

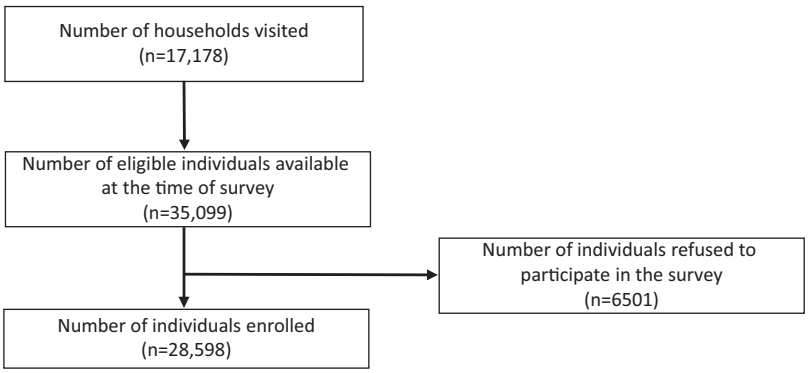

Figure 1. Flowchart of participant enrollment.

2021). In this study, seroprevalence was also calculated using lower COI of >0.54 for the Abbott assay and 0.32 for the Siemens IgG assay, as suggested by Irsara et al. (2021). In addition, seroprevalence was estimated using the lowest values of sensitivity (90.8% for the Abbott assay and 78.8% for the Siemens assay) and specificity (99.3% for Abbott assay and 100% for the Siemens assay) estimated through external validation studies (see online Supplementary material).

Protection of human participants

Written informed consent was obtained from individuals aged ≥18 years, and assent was obtained from children aged between 10 and 17 years, with written informed consent from their parents or guardians, before the survey (Indian Council of Medical Research, 2017). The Institutional Human Ethics Committee of ICMR National Institute of Epidemiology, Chennai approved the study protocol.

Results

Seroprevalence among the general population

In total, 17,178 households from 700 clusters in 70 districts were visited. Of the 35,099 individuals who were available at the time of the visit of the survey teams, 28,598 (81.5%) consented to participate (Figure 1).

The mean age of the study participants was 38.2 (SD 16.4) years. Nearly three-quarters of the participants (n = 21,187, 74.1%) were residing in rural areas, 51.6% (n = 14,763) were female, and 15.2% (n = 4333) had an occupation with a higher risk of exposure to potentially infected persons. Of the 1889 (6.6%) participants who reported history of COVID-19 symptoms since March 2020, 474 (25.1%) reported seeking medical care. The main symptoms reported by participants were cough (63.7%), fever (52.4%), tiredness/fatigue (13%), sore throat (12.4%), shortness of breath (11.2%), new loss of smell (4.2%) and new loss of taste (3.5%) (see online Supplementary material). In total, 3232 (11·4%) individuals reported having been tested for SARS-CoV-2 by RT-PCR or rapid antigen test in the past, of whom 287 (8.9%) reported a positive result (Table 1).

Of the 28,598 individuals tested, 4585 (16%) had IgG antibodies against the N protein and 6647 (23.2%) had IgG antibodies against the S1-RBD protein. Weighted and assay-characteristic-adjusted seroprevalence of IgG antibodies against the N and S1-RBD proteins were 14.3% (95% CI 13.6–15.0%) and 21.5% (95% CI 20.4–22.6%), respectively. Overall, 7436 individuals had IgG antibodies against either the N protein or the S1-RBD protein, with weighted and assay-characteristic-adjusted seroprevalence of 24.1% (95% CI 23.0–25.3%) (Table 2). Seroprevalence in districts ranged between 4.9% (20/407) in Mahisagar (Gujarat) and 44.4% (176/396) in Bijapur (Chhattisgarh) (see online Supplementary material).

Overall seroprevalence did not differ by sex (males 23.2%, 95% CI 22.1–24.5%; females 24.9%, 95% CI 23.7–26.3%). Seroprevalence was lowest among individuals aged 18–44 years and was similar among other age groups. Individuals residing in rural areas had significantly lower seroprevalence (21.4%, 95% CI 20.3–22.6%) compared with those living in urban non-slum areas (29.5%, 95% CI 27.0–32.1%) and urban slum areas (34.7%, 95% CI 31.2–38.5%) (Table 3, see online Supplementary material).

Seropositivity was higher among individuals who reported COVID-19-related symptoms (28.7%, 95% CI 26.1–31.4%), and had contact with COVID-19 cases, either within (42.5%, 95% CI 36.7–48.3%) or outside (24.9%, 95% CI 20.0–30.6) the household.

Of the 287 individuals who reported COVID-19 infection by rapid antigen test or RT-PCR, 178 (63.6%, 95% CI 57.2–69.4%) were seropositive (Table 3). Seroprevalence had a positive non-linear correlation with the cumulative incidence of reported COVID-19 cases in the 70 districts (correlation coefficient 0.352) (see online Supplementary material).

Seroprevalence among adults

In order to compare seroprevalence among adults between the three serosurveys, 16,565 adults, one per household, were selected at random from the database. Of these, 2657 had IgG antibodies against the N protein with weighted and adjusted seroprevalence of 14.3% (95% CI 13.5–15.1%). The weighted seroprevalence of IgG antibodies against either the N protein or the S-RBD protein was 24.3% (95% CI 23.1–25.6%).

Burden of SARS-CoV-2 infection in December 2020

Applying the overall seroprevalence to the population aged ≥10 years, it was estimated that 271,404,207 (95% CI 259,016,464–284,918,110) individuals in India had been infected by December 2020. With 10,027,311 and 10,181,165 COVID-19 cases reported by 12 December and 19 December 2020, respectively, it was estimated that there were 27.1 (95% CI 25.8–28.4) and 26.7 (95% CI 25.4–28.0) infections per reported case of COVID-19 (Table 4).

Sensitivity analysis

Using the lower cut-off values, the overall seroprevalence of SARS-CoV-2 infection was 37.4% (95% CI 35.9–38.8) (see online Supplementary material). Considering the lowest values of

Table 1
Characteristics of study participants.

Characteristics	General population *n* (%)	Healthcare workers *n* (%)
Age (years)	*n* = 28,598	*n* = 7385
10–17	2290 (8.0)	–
18–44	16,333 (57.1)	5351 (72.5)
45–60	6938 (24.3)	1956 (26.4)
>60	3037 (10.6)	78 (1.1)
Mean age (SD)	38.2 (16.4)	38.0 (10.2)
Sex	*n* = 28598	*n* = 7385
Male	13,817 (48.3)	3175 (43.0)
Female	14,763 (51.6)	4206 (56.9)
Other	18 (0.1)	4 (0.1)
Residence	*n* = 28598	–
Rural	21,187 (74.1)	–
Urban non-slum	4821 (16.9)	–
Urban slum	2590 (9.0)	–
Type of healthcare worker	–	*n* = 7382
Doctors/nurses	–	2014 (27.3)
Paramedical staff	–	2684 (36.4)
Field staff	–	2031 (27.5)
Admin staff	–	653 (8.8)
COVID-19 related symptoms	*n* = 28,598	*n* = 7385
History of COVID-19 symptoms since March 2020	1889 (6.6)	1066 (14.4)
Medical care sought by symptomatic cases	474/1889 (25.1)	557/1066 (52.3)
History of hospitalization	73/474 (15.4)	173/557 (31.1)
Occupation	*n* = 28575	–
High risk of exposure to COVID-19	4333 (15.2)	–
History of contact with known COVID-19 case	*n* = 28,576	–
Within household	598 (2.1)	–
Outside household	297 (1.0)	–
No history of contact with known COVID-19 case	27,681 (96.9)	–
History of contact with known COVID-19 case	–	*n* = 7382
Health facility	–	3120 (42.3)
Within household	–	130 (1.8)
Outside health facility/household	–	191 (2.6)
No history of contact with known COVID-19 case	–	3941 (53.3)
Ever tested for COVID-19	*n* = 28,598	*n* = 7385
RT-PCR	1028 (3.6)	1663 (22.5)
Rapid antigen test	1477 (5.2)	1509 (20.4)
RT-PCR and rapid antigen test	330 (1.2)	1402 (19.0)
Don't know the type of test	397 (1.4)	126 (1.7)
Not tested for COVID-19	25,366 (88.6)	2685 (36.4)
Results of COVID-19 testing	*n* = 3232	*n* = 4700
Reported positive for COVID-19	287 (8.9)	664 (14.1)

SD, standard deviation; COVID-19, coronavirus disease 2019; RT-PCR, reverse transcriptase polymerase chain reaction.

Table 2
Seroprevalence (%) of immunoglobulin G antibodies against severe acute respiratory syndrome coronavirus-2 infection, India, August–September 2020.

	General population aged ≥10 years			Healthcare workers
	Anti-N antibodies	Anti-S1-RBD antibodies	Anti-N or anti-S antibodies	Anti-S1-RBD antibodies
Number of individuals tested	28,598	28,598	28,598	7385
Number of positives	4585	6647	7436	1899
Unweighted prevalence[a] (%)	16.0 (15.3–16.8)	23.2 (22.2–24.3)	26.0 (25.0–27.1)	25.7 (23.7–27.9)
Weighted prevalence[b] (%)	14.6 (13.9–15.3)	21.7 (20.6–22.8)	24.6 (23.5–25.7)	–
Adjusted prevalence[c] (%)	14.3 (13.6–15.0)	21.5 (20.4–22.6)	24.1 (23.0–25.3)	25.6 (23.5–27.8)

N, nucleocapsid protein; S1-RBD, spike protein of the receptor binding domain.
[a] Adjusted for clustering.
[b] Weighted for sampling weights.
[c] Adjusted for test performance.

sensitivity and specificity obtained from external validation studies, the overall seroprevalence was 24.5% (95% CI 23.4–25.7).

Seroprevalence among HCWs

In total, 7385 individuals working in 199 subdistrict-level public health facilities in 70 districts were included in the survey. Their mean age was 38 (SD 10.2) years and 4206 (56.9%) were female. Approximately one third (*n* = 2684, 36.4%) were paramedical workers and 27.3% (*n* = 2014) were doctors/nurses (Table 1). Overall, 1066 (14.4%) reported a history of COVID-19 symptoms since March 2020, and 3441 (46.7%) reported exposure to a case of COVID-19. In all, 664 (14.1%) of the 4700 individuals who reported COVID-19 testing by rapid antigen testing or RT-PCR were positive (Table 1).

Test-performance-adjusted seroprevalence of IgG antibodies against SARS-CoV-2 infection was 25.7% (95% CI 23.7–27.9) (Table 2). Seroprevalence did not differ between different HCW

Table 3
Seroprevalence (%) of immunoglobulin G antibodies against severe acute respiratory syndrome coronavirus-2 infection by demographic characteristics, India, December 2020–January 2021.

Characteristics	General population aged ≥10 years (n = 28,598)			Healthcare workers (n = 7385)		
	No. tested	No. positive (anti-N/ anti-S1-RBD antibodies)	Weighted and test-performance-adjusted seroprevalence % (95% CI)	No. tested	No. positive (only S1-RBD)	Test-performance-adjusted seroprevalence % (95% CI)
Sex						
Male	13,817	3503	23.2 (22.1–24.5)	3175	810	25.4 (23.5–27.3)
Female	14,763	3928	24.9 (23.7–26.3)	4206	1089	25.8 (23.0–28.7)
Other	18	5		4	0	–
Age (years)						
10–17	2290	634	27.2 (24.9–29.4)	–	–	–
18–44	16,333	3936	22.2 (21.1–23.4)	5351	1295	24.0 (21.9–26.3)
45–60	6938	2011	26.7 (25.2–28.2)	1956	587	29.9 (27.1–32.9)
>60	3037	855	26.3 (24.3–28.3)	78	17	21.6 (13.8–32.2)
Area of residence						
Rural	21,187	4997	21.4 (20.3–22.6)	–	–	–
Urban non-slum	4821	1520	29.5 (27.0–32.1)	–	–	–
Urban slum	2590	919	34.7 (31.2–38.5)	–	–	–
Occupation with high risk of exposure to COVID-19						
Yes	4333	1036	21.7 (20.1–23.3)			
No	24,242	6391	24.5 (23.4–25.8)			
Type of healthcare worker	–	–	–			
Doctors/nurses	–	–	–	2014	537	26.6 (23.5–29.7)
Paramedical staff	–	–	–	2684	681	25.3 (22.8–27.9)
Field staff	–	–	–	2031	518	25.4 (22.5–28.4)
Admin staff	–	–	–	653	162	24.6 (20.5–29.4)
History of COVID-19-related symptoms since 1 March 2020						
Yes	1889	651	28.7 (26.1–31.4)	1066	407	38.1 (32.9–43.5)
No	26,709	6785	23.8 (22.7–24.9)	6319	1492	23.4 (21.4–25.7)
History of contact with a known COVID-19 case						
Within household	598	225	42.5 (36.7–48.3)	–	–	–
Outside household	297	96	24.9 (20.0–30.6)	–	–	–
No	23,221	5850	23.4 (22.3–24.5)	–	–	–
Don't know	4460	1256	25.6 (23.4–27.8)	–	–	–
History of contact with a known COVID-19 case						
Health facility	–	–	–	3120	864	27.6 (24.8–30.4)
Within household	–	–	–	130	46	35.3 (26.7–44.9)
Outside health facility/ household	–	–	–	191	57	29.7 (21.3–39.7)
No	–	–	–	3255	751	22.9 (20.2–25.9)
Don't know	–	–	–	686	180	26.1 (22.9–29.5)
Previously tested for COVID-19						
RT-PCR	1028	357	29.0 (25.9–32.2)	1663	477	28.6 (25.2–32.2)
Rapid antigen test	1477	485	26.5 (23.6–29.6)	1509	415	27.4 (23.7–31.3)
RT-PCR and rapid antigen test	330	123	29.6 (24.5–35.1)	1402	386	27.4 (23.8–31.3)
Don't know the type of test	397	128	20.3 (15.6–26.2)	126	23	18.1 (13.2–24.1)
Not tested	25,344	6334	23.8 (22.7–24.9)	2682	597	22.1 (19.7–24.7)
Results of COVID-19 testing						
Reported positive for COVID-19	287	178	63.6 (57.2–69.4)	664	395	59.4 (54.0–64.6)
Reported negative for COVID-19	2526	778	27.6 (25.2–30.2)	3982	900	22.4 (20.0–25.1)
Don't know	419	137	30.8 (25.3–36.8)	54	6	10.9 (4.2–25.4)

CI, confidence interval; COVID-19, coronavirus disease 2019; RT-PCR, reverse transcriptase polymerase chain reaction; N, nucleocapsid protein; S1-RBD, spike protein of the receptor binding domain.

Table 4
Estimated number of infections among individuals aged ≥10 years and infection to case ratio.

	Estimate (95% CI) by N seroprevalence	Estimate (95% CI) by S seroprevalence	Estimate (95% CI) by N/S seroprevalence
Number of infections	160,556,739 (152,641,970–168,471,508)	242,124,085 (229,736,342–254,511,829)	271,404,207 (259,016,464–284,918,110)
Number of reported COVID-19 cases (12 Dec)	10,027,311	10,027,311	10,027,311
Infection to case ratio (12 Dec)	16.0 (15.2–16.8)	24.1 (22.9–25.4)	27.1 (25.8–28.4)
Number of reported COVID-19 cases (19 Dec)	10,181,165	10,181,165	10,181,165
Infection to case ratio (19 Dec)	15.8 (15.0–16.5)	23.8 (22.6–25.0)	26.7 (25.4–28.0)

CI, confidence interval; COVID-19, coronavirus disease 2019; N, nucleocapsid protein; S, spike protein.

categories. Seroprevalence did not differ by age and sex. Seroprevalence was higher among HCW who reported COVID-19 symptoms in the past, those who reported contact with a COVID-19 case within the household, and those who reported a positive result on rapid antigen testing or RT-PCR (Table 3).

Discussion

The findings of the third serosurvey indicate that nearly 24% of India's population aged ≥10 years had been exposed to SARS-CoV-2 infection by December 2020, with an estimated 271 million infections. Seroprevalence did not differ by sex, but was lower among adults aged 18–44 years and in rural areas compared with urban areas. The results also indicate that approximately one-quarter of HCWs working in the peripheral public sector health facilities were positive for IgG antibodies.

Antibody assays were used to detect IgG against the N and S1-RBD proteins of SARS-CoV-2 in this survey. N-protein assays are reported to be more sensitive than S1 assays for the detection of antibodies in mildly infected patients that are reported to show absent or delayed, and lower SARS-CoV-2 antibody responses (Özçürümez et al., 2020; van Tol et al., 2020). It has been shown that the anti-N antibodies appear earlier than the S antibodies, and may therefore increase the clinical sensitivity of the assay if samples are drawn early (Rikhtegaran Tehrani et al., 2020). In the third serosurvey, 800 individuals were reactive for the N-protein but negative for the S1-RBD protein, possibly suggesting early infections. The IgG antibody response against different viral antigens is heterogeneous in nature and the results do not always correlate with each other (McAndrews et al., 2020). Therefore, the detection of antibodies against two different antigens, with high sensitivity and specificity, is needed to confirm the findings and avoid false-negative results in surveillance studies (Irsara et al., 2021).

Seroprevalence studies provide information about the extent of transmission in the past, and help predict the future course of the pandemic (World Health Organization, 2020a; Chen et al., 2021). Seroprevalence of IgG antibodies against SARS-CoV-2 among individuals aged ≥10 years in India increased from 6.6% in August 2020 to 24.1% in December 2020. The prevalence of IgG antibodies against the N protein between the two serosurveys increased at least 2.2-fold. Serum samples from the previous serosurvey were not tested for anti-S1-RBD IgG antibodies. During the same period, the reported number of COVID-19 cases in India has increased 3.5-fold. Anti-N antibody seropositivity has decreased in 15 of the 70 survey districts by 10.7% to 63.4%, with the steepest decline in Vizianagaram (Andhra Pradesh), Chennai (Tamil Nadu) and Ganjam (Odisha) districts. In the remaining 55 districts, seropositivity to anti-N antibodies has increased 1.04–76-fold (see online Supplementary material). This increase in seroprevalence is consistent with the increase in the number of COVID-19 cases reported between August and December 2020 in these districts (see online Supplementary material).

In the third serosurvey, seroprevalence was significantly lower in the 18–44 years age group, whereas in the second serosurvey, prevalence was similar across age groups. Between August and December 2020, the age-specific seroprevalence of anti-N antibodies increased 1.8-fold among individuals aged 18–44 years and 2.6–3.1-fold in the remaining age groups (see online Supplementary material).

Lower seroprevalence in the active and productive age group compared with other age groups is not consistent with the transmission pattern of COVID-19. This age group was exposed to infection early in the pandemic, as reflected by the relatively high incidence of COVID-19 among this age group between January and April 2020 (ICMR COVID Study Group, 2020). Therefore, the lower seroprevalence found in this age group could be due to relatively higher waning of IgG antibodies compared with other age groups. It is noteworthy that 81% of individuals with RT-PCR-confirmed infection were seropositive during the second survey, compared with 63% during the third serosurvey.

Higher seroprevalence of SARS-CoV-2 infection was found in urban areas compared with rural areas in the third serosurvey. Although this pattern was similar to the second serosurvey in August 2020, seroprevalence did not differ between slum and non-slum urban areas, as was observed in August 2020. Between August and December 2020, the increase in seroprevalence was highest in rural areas (2.5-fold), followed by urban non-slum areas (1.93-fold) and urban slum areas (1.07-fold), reflecting the varied distribution of susceptible populations in these areas. The declining trend in the reported number of COVID-19 cases in India from mid-September 2020 points to a reduction in transmission, which could be attributed to higher seroprevalence in urban slum and non-slum areas, considering these locations to be the drivers of the epidemic in the country (Malani et al., 2021b). The findings of the third serosurvey also indicate that a large proportion of individuals in rural areas remain susceptible to SARS-CoV-2 infection. A similar finding was observed in the recent serosurvey conducted in Karnataka and Tamil Nadu (Malani et al., 2021a; Mohanan et al., 2021).

In India, several cities and states have conducted serosurveys. Metropolitan cities such as Delhi, Mumbai, Pune, Chennai, Ahmedabad and Hyderabad have reported seroprevalence ranging between 17.6% and 56% at different timepoints (see online Supplementary material). Tamil Nadu and Kerala conducted serosurveys covering all districts in October–November 2020 and February 2021, respectively. Seroprevalence reported in Chennai, Coimbatore and Tiruvannamalai districts of Tamil Nadu were comparable to the present survey. The higher seroprevalence in Palakkad, Ernakulam and Thrissur districts of Kerala found in the present survey compared with the Kerala serosurvey could be due to the use of assays for antibodies against the N-protein alone in the Kerala serosurvey.

Seroprevalence among HCWs (25.6%) observed in this study was much higher compared with the 8.7% prevalence estimated in a systematic review and meta-analysis among HCWs (Galanis et al.,

2021). Comparable seroprevalence among clinical, paramedical, field and administrative workers in health facilities and by place of contact with known COVID-19 case suggests widespread transmission of SARS-CoV-2 in the survey areas.

This study has several limitations. First, the participation of children aged 10–17 years in this survey was lower than the census-based age distribution in India (Office of the Registrar General and Census Commissioner, New Delhi and Government of India, 2011). According to the 2011 census, approximately 21% of the population were aged 10–17 years, whereas 8% of the study population were aged 10–17 years (see online Supplementary material). The under-representation of children and over-representation of adults in the survey could lead to underestimation of the true seroprevalence if one expects a real difference in the risk of exposure to SARS-CoV-2 across age groups. Further, 26% of the study clusters in the present survey were from urban areas, whereas, according to the 2011 census, 31% of the population of India reside in urban areas. Although the proportion of clusters from urban areas in this survey was slightly lower than the national average, this survey was representative of India overall. Approximately 18.5% of eligible individuals declined to participate in this survey. If this non-response was not at random, this could introduce selection bias. Second, different assays were used to measure IgG antibodies in the three serosurveys. In the first serosurvey, a laboratory assay which detected IgG antibodies against the whole cell antigen was used, and positive sera were retested with an assay which detected antibodies against the S1 domain of the S protein of SARS-CoV-2 (Murhekar et al., 2020). In the second serosurvey, a laboratory assay which detected IgG antibodies against the N protein of SARS-CoV-2 was used (Murhekar et al., 2021). As antibodies against the N protein of SARS-CoV-2 have been shown to decline faster over a period of time, the actual seroprevalence may have been under-estimated, and thereby the actual number of infections (Ripperger et al., 2020; Bolotin et al., 2021). In order to overcome these limitations, the serum samples were tested with both anti-N and anti-S1 assays in the third survey. Third, the infection to case ratio was estimated based on the reported number of cases of COVID-19. The completeness of reporting of COVID-19 cases could vary between Indian states.

In conclusion, the findings of the third nationwide serosurvey indicate that nearly one in four individuals aged $\geq$10 years from the general population as well as HCWs had been exposed to SARS-CoV-2 by December 2020 in India. Seroprevalence increased between August and December 2020, and the decline in the number of COVID-19 cases seen in India since mid-September could be on account of higher seroprevalence in urban areas. As three-quarters of the population are still susceptible, it is necessary to continue ongoing surveillance for COVID-19 cases, especially in rural areas. It is also necessary to continue implementation of non-pharmaceutical interventions, such as physical distancing, use of face masks and hand hygiene. The Government of India has initiated COVID-19 vaccination since January 2021, targeting healthcare and frontline workers in the first phase and individuals aged >60 years in the second phase (Ministry of Health and Family Welfare, Government of India, 2020). As a higher proportion of rural residents are susceptible to infection, and considering limited healthcare facilities in rural areas, especially oxygen beds (Kumar et al., 2020), elderly populations in rural areas may be prioritized for COVID-19 vaccination.

Author contributions

MVM, TB, JWVT, MSaK, KR, DCSR, SP and BB undertook the study design. TB, MSaK, JWVT, SSe, RSa, AT, SA, RB, SDB, AKB, VC, DD, AKD, KRD, VD, GRD, SMSK, MSuK, AL, MM, AMa, CR, JT, RY, RA, KA, DKB, PB, DB, JB, ASC, DC, AC, HD, SD, RD, DE, PG, IH, RKH, BJ, AK, SK, NNK, JSK, AK, NK, VGVK, GGJN, GM, NKM, AM, KN, AN, ARN, AKP, GVP, MAQ, SDR, AR, SSa, RS, KS, VKS, HBS, PKS, PS, RSi, NS, DSV, AV, VCW, SurY, SY, KZ, AC, AD, RSD, SD, RK, AMK, KN, SN, CP, KP, SaP, ShP, HR, TR, YKS and ShS coordinated the field operations. CPGK coordinated the laboratory processing and testing of samples. VS, JWVT, MVM, RSa and MSaK performed data analysis. MVM, TB, JWVT, MSaK, KR, SP, DCSR and BB performed data interpretation. MVM, TB, VS, JWVT, RSa and MSaK accessed and verified the data. MVM, TB, MSaK and JWVT wrote the first draft of the manuscript. All authors approved the final version of the manuscript.

Conflict of interest

None declared.

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Ethical approval

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Uttar Pradesh

Akhileshwar Sharda, Sanidhya Bhargava, Dilip Singh, Vijay Kumar, Naresh Dhakar, Vinay Kumar, Akash Yadav, Deshdeepak Gautam, Swati Singh, Brijesh Maurya, Shaurabh Kumar, Manisha Dhakar, Sheena Singh, Nitesh Kumar, Renu Kanwar, Rahul Yadav, Narendra Yadav, Rahul Kumar, Himalaya Kumar, Raju, Balijeet Sodhi, Rajesh Jain, Shivanka Gaur, Deepak Ohari, Tikam Singh, Saubhagya Prakash, Haridutt Nemi, Dechen Yangdol, Upendra Singh, Harshit Kumar, Amit Yadav, Mohit Tiwari, Gopal Prasad, Sapna Yadav, Basudev Singh, Deepak Babu, Rahul Kumar, Chakrapani Katara, Chandra Pratap Singh, Simran Kaur Bhojwani, Manish Kumar, P. Vedival, Rahul Gond, Prabhat Kumar, Hariom Kushwah, Gani Aftridi, Nistha Verma, Veer Vishal, Rakesh Sharma, K. Uday, Saurabha Yadav, Navneet Rajput, Satya Prakash, Mohit Sharma, Sunny Sharma, Santosh Kushwah, Akhalesh Yadav, Shimala Rathore, Prabha Shakya, Vikas Sabharwal, Ravinder Singh, Sushil Chander, Manoj Sharma, Ramesh Kunwar, Sukhwant Singh, Satyvrat Vaidya, Raman Sharma, Pankaj Singh, Manu Jain, Archana Srivastava, Manoj Bahukhandi, Ashish Gusain, Arjit Kumar, Dhruv Gopal, V. Mehta, Vineet Kumar Shukla, R.K. Gautam, Anil Gautam, J. S. Rawat, Bhupinder Singh, Himanshu Sharma, Madhu Kumari, Rajesh Mourya, R.S. Yadav, Surinder Singh, Agam Jain, Raju Kumavat, Sandeep Patil, Pradhumn Katara, Namrata Soni, Prashant Upadhyaya, Praveen Pachauri, Ajay Rawat, Sanjay Chopra, Jyoti Mishra, Mohammed Husain, Debi Lal, Amit Mohan Prasad, Ghanshyam Singh, Atul Kumar Singhal, Ajay Singh Gautam, Vinay Dange, Shri Prakash Agrawal, Satish Chandra Singh, Birendra Panchal, Vishal Yadav, Mukesh Kumar Mishra, Ravi Shankar Singh, Kamlesh Sah, Sonal Rajput, Sushil Pal, Jaibardhan Siddharth, Ravi Nishad, Rohit Baghel, Punit Kumar, Abhishek Kumar Mishra, Avdhesh Kumar, Anu Gunj, Pawan Kumar, Anurag Srivastava, Vipul Kumar, Kiran, Akash Kushwaha, Vinod Kumar, Ram Poojan Yadav, Mayank Badola and Santhosh Gupta.

West Bengal

Falguni Debnath, Suman Kanungo, Gargi Dutta Bhattacharyya, Subrata Biswas, Ajay Chakraborty, Jayesh Mehta, Bandita Sengupta, Abhijit Dey, Arup Chakrabortty, Subhendu Kumar Ray, Subhadip Bhunia, Amlan Datta, Debasish Roy, Shyamal Soren, Jagannath Sarkar, Somnath Mukherjee, Prakash Chandra Mridha, Girish Chandra Bera, Nitai Mandal, Santanu Sahu, Atrayee Chakraborty, Rabiul Islam Gayen, Dilip Biswas, Samudra Sengupta, Barnaman Tudu, Poulami Sen, Anjan Kumar Mallick, Saptarshi Bannerjee, Biswadeep Sengupta, Soumen Jana, Joyeeta Bhattacharyya, Medhavi Manish, Biswajit Namasharma, Chandan Ghosh, Debarati Chakraborty, Kunal Maiti, Milan Barman, Pintu Manik, Priya Rana, Purnima Roy, Rajani Kurmi, Rocky Ansari, Sanglap Maity, Somobrota Naskar, Souptik Jana, Sourav Pradhan, Bishakha Pramanik, Dipannita Sardar, Sujit Kumar Shreshta, Arpita Das, Shrikant Shankar Gawali, Sriparna Garai, Swarnendu Sasmal, Ujjal Maitra, Saiful Gazi, Joydeep Banerjee, Rupali Ghosh, Nawaid Ali, Pokhraj Dey, Chandan Ghosh, Susanta Bera, S.K. Monirul Jaman, Shrija Ghosh, Dev Kumar Dolai, Purnima Das, Wasim Reza and Rajesh Das.

Appendix A. Supplementary data

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References

Bolotin S, Tran V, Osman S, Brown KA, Buchan SA, Joh E, et al. SARS-CoV-2 seroprevalence survey estimates are affected by anti-nucleocapsid antibody decline. J Infect Dis 2021;223:1334–8.

Center for Devices and Radiological Health. EUA authorized serology test performance. Silver Spring, MD: FDA; 2021.

Chen X, Chen Z, Azman AS, Deng X, Sun R, Zhao Z, et al. Serological evidence of human infection with SARS-CoV-2: a systematic review and meta-analysis. Lancet Glob Health 2021;9:e598–609.

FETP Network – Chennai, India. COVID-19 Resource Center, Epicurve by state. FETP Network India; 2021 Available at: http://covidindiaupdates.in/epicurve_state.php. [Accessed 19 February 2021].

Galanis P, Vraka I, Fragkou D, Bilali A, Kaitelidou D. Seroprevalence of SARS-CoV-2 antibodies and associated factors in healthcare workers: a systematic review and meta-analysis. J Hosp Infect 2021;108:120–34.

ICMR COVID Study Group. Laboratory surveillance for SARS-CoV-2 in India: performance of testing and descriptive epidemiology of detected COVID-19, January 22–April 30, 2020. Indian J Med Res 2020;151:424–37.

Indian Council of Medical Research. National ethical guidelines for biomedical and health research involving human participants. New Delhi: ICMR; 2017.

Irsara C, Egger AE, Prokop W, Nairz M, Loacker L, Sahanic S, et al. Evaluation of four commercial, fully automated SARS-CoV-2 antibody tests suggests a revision of the Siemens SARS-CoV-2 IgG assay. Clin Chem Lab Med 2021;59:1143–54.

Kumar A, Rajasekharan Nayar K, Koya SF. COVID-19: challenges and its consequences for rural health care in India. Publ Health Pract 2020;1:100009.

Long Q-X, Liu B-Z, Deng H-J, Wu G-C, Deng K, Chen Y-K, et al. Antibody responses to SARS-CoV-2 in patients with COVID-19. Nat Med 2020;26:845–8.

Malani A, Ramachandran S, Tandel V, Parasa R, Imad S, Sudharshini S, et al. SARS-CoV-2 seroprevalence in Tamil Nadu in October–November 2020. MedRxiv 2021a; 2021.02.03.21250949.

Malani A, Shah D, Kang G, Lobo GN, Shastri J, Mohanan M, et al. Seroprevalence of SARS-CoV-2 in slums versus non-slums in Mumbai, India. Lancet Glob Health 2021b;9:e110–1.

McAndrews KM, Dowlatshahi DP, Dai J, Becker LM, Hensel J, Snowden LM, et al. Heterogeneous antibodies against SARS-CoV-2 spike receptor binding domain and nucleocapsid with implications for COVID-19 immunity. JCI Insight 2020;5: e142386.

Ministry of Health and Family Welfare, Government of India. COVID-19 vaccines: operational guidelines. New Delhi: MHFW; 2020.

Ministry of Home Affairs, Government of India. Government of India issues orders prescribing lockdown for containment of COVID-19 epidemic in the country. New Delhi: MHA; 2021 Available at: https://pib.gov.in/Pressreleaseshare.aspx?PRID=1607997. [Accessed 12 May 2021].

Ministry of Home Affairs, Government of India. Guidelines for phased re-opening (Unlock 1). As per the Ministry of Home Affairs Order No. 40-3/2020-DM-I (A) dated 30th May, 2020. New Delhi: MHA; 2020.

Mohanan M, Malani A, Krishnan K, Acharya A. Prevalence of SARS-CoV-2 in Karnataka, India. JAMA 2021;325:1001–3.

Murhekar MV, Bhatnagar T, Selvaraju S, Rade K, Saravanakumar V, Vivian Thangaraj JW, et al. Prevalence of SARS-CoV-2 infection in India: findings from the national serosurvey, May–June 2020. Indian J Med Res 2020;152:48–60.

Murhekar MV, Bhatnagar T, Selvaraju S, Saravanakumar V, Thangaraj JWV, Shah N, et al. SARS-CoV-2 antibody seroprevalence in India, August–September, 2020: findings from the second nationwide household serosurvey. Lancet Glob Health 2021;9:e257–66.

Office of the Registrar General and Census Commissioner, New Delhi and Government of India. 2011 census: age structure and marital status. Office of the Registrar General and Census Commissioner, Government of India; 2011.

Özçürümez MK, Ambrosch A, Frey O, Haselmann V, Holdenrieder S, Kiehntopf M, et al. SARS-CoV-2 antibody testing-questions to be asked. J Allergy Clin Immunol 2020;146:35–43.

Piccoli L, Ferrari P, Piumatti G, Jovic S, Rodriguez BF, Mele F, et al. Risk assessment and seroprevalence of SARS-CoV-2 infection in healthcare workers of COVID-19 and non-COVID-19 hospitals in Southern Switzerland. Lancet Region Health Europe 2021;1:100013.

Rikhtegaran Tehrani Z, Saadat S, Saleh E, Ouyang X, Constantine N, DeVico AL, et al. Performance of nucleocapsid and spike-based SARS-CoV-2 serologic assays. PLoS One 2020;15:e0237828.

Ripperger TJ, Uhrlaub JL, Watanabe M, Wong R, Castaneda Y, Pizzato HA, et al. Orthogonal SARS-CoV-2 serological assays enable surveillance of low-prevalence communities and reveal durable humoral immunity. Immunity 2020;53:925–933.e4.

Sempos CT, Tian L. Adjusting coronavirus prevalence estimates for laboratory test kit error. Am J Epidemiol 2021;190:109–15.

van Tol S, Mögling R, Li W, Godeke G-J, Swart A, Bergmans B, et al. Accurate serology for SARS-CoV-2 and common human coronaviruses using a multiplex approach. Emerg Microbes Infect 2020;9:1965–73.

World Health Organization. Population-based age-stratified seroepidemiological investigation protocol for coronavirus 2019 (COVID-19) infection, 26 May 2020. Version 2.0. Geneva: WHO; 2020.

World Health Organization. Weekly epidemiological update – 5 January 2021. Geneva: WHO; 2020 Available at: https://www.who.int/publications/m/item/weekly-epidemiological-update—5-january-2021. [Accessed 12 May 2021].