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Socioeconomic determinants potentially underlying differential global SARS-CoV-2 testing capacity: an ecological study

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ABSTRACT

Objectives To analyse the relationships between SARS-CoV-2 laboratory testing capacity (TC) and socioeconomic factors (wealth, governance and social inequality) across 109 countries in 2020–2021, to identify potential determinants of global disparities in TC during the COVID-19 pandemic.

Design An ecological study using regression analyses to explore the associations between TC and socioeconomic determinants within and across global regions.

Setting/participants Data from 109 countries from Our World in Data, the WHO, the United Nations and others grouped into six geographic and sociodemographic regions (global burden of disease regions), were analysed separately for the years 2020–2021 based on differential vaccine availability and country-level responses throughout the pandemic.

Outcome measures Relationships between SARS-CoV-2 TC and factors such as vaccination rates, wealth, vulnerable employment (VE), gender and income inequality within and across world regions in 2020–2021.

Results TC increased a minimum of 2.1-fold for 'Sub-Sahara' (median TC 1800–3700 tests) to a maximum of 4.9-fold for 'Asia and Oceania' (4500–22 000) between 2020 and 2021. Factors associated with TC among the socioeconomic variables included VE that was associated with reduced TC both in 2020 (relative change (RC) –43%; 95% CI –57% to –25%) and 2021 (RC –46%; 95% CI –62% to –24%) and employment-to-population ratio that had a positive effect on TC in 2021 (RC 27%; 95% CI 44% to 55%). Socioeconomic variables showed similar patterns for both the established measles–mumps–rubella and the new COVID-19 vaccines. Region-level analyses revealed stark heterogeneity in the associations between socioeconomic variables and TC between the analysed years (2020 vs 2021) and across regions. Region-specific trends showed that in Latin America and Asia/Oceania, TC was linked to health expenditure in both analysed years (RC_{2020}: 199%; 95% CI 74% to 405%; RC_{2021}: 142%; 95% CI 67% to 24%). VE was associated with decreased TC in the 'high-income', 'Central Europe' and 'Sub-Saharan' regions.

Conclusions Socioeconomic and gender inequalities play a significant role in determining SARS-CoV-2 TC. These inequalities underscore the necessity of ensuring equitable access to health services and targeted public health interventions, particularly in resource-limited settings, to improve health outcomes and pandemic preparedness. Socioeconomic and gender disparities can exacerbate health inequalities and hinder the effectiveness of public health policies in a globally interconnected world.

STRENGTHS AND LIMITATIONS OF THIS STUDY

⇒ Analysing potential drivers of laboratory testing capacity (TC) aids interpretation of differences in COVID-19 management globally, including resource-limited settings.
⇒ The study includes data from 109 countries, representing a diverse range of regions and socioeconomic conditions, providing a broad perspective on global disparities in SARS-CoV-2 TC.
⇒ The use of multivariable regression models, including negative binomial models to account for overdispersion on count data, allows the analysis of the relationships between socioeconomic factors and TC across regions.
⇒ Data quality and reporting may vary between countries, especially in resource-limited settings, potentially introducing biases or inconsistencies in the analysis of TC and vaccination.
⇒ The ecological design of the study limits its ability to assess any causality regarding the association between socioeconomic factors and TC and additionally cannot assess more fine-grained temporal variations.

INTRODUCTION

Reported COVID-19 mortality and incidence vary considerably among countries and world regions[1] and are potentially affected by a complex interplay of multiple social, economic and political drivers, such as wealth, access to healthcare and quality of infectious disease surveillance, among others.[2] Apart from vaccination coverage and baseline morbidity, the availability of COVID-19 laboratory tests has been considered to impact mortality and incidence estimates, yet this interaction remains poorly understood, particularly at the regional or multinational level, which includes relatively less studied resource-limited settings.[3] The laboratory testing capacity (TC) is defined as the number of diagnostic tests done in a population of defined size (https://ourworldindata.org/).[4] Since COVID-19-related incidence and mortality statistics guide the timing and implementation of intervention strategies, including vaccination programmes and non-pharmaceutical interventions such as lockdowns,[5] it is essential to understand the factors underlying differences in TC between countries and regions.

Previous research has associated TC with a country's economic wealth,[1] particularly because of the widespread use of PCR, a method requiring cost-intensive laboratory infrastructure, trained personnel and reagents, all of which depend on the availability of resources.[6] Conversely, weak pandemic management, particularly the lack of coordination between national and local governments, has been shown to hinder laboratory testing, as well as the acceptance of individuals to be tested.[7] Additionally, the absence of remote work opportunities and limited access to social programmes aimed at vulnerable employment (VE) have been assumed to constrain the decision to be PCR tested since a positive test result may imply social isolation and the impossibility of earning sustenance, all together negatively impacting TC.[8] In sum, current knowledge discusses TC as a function of wealth, governance and social inequality within countries. These studies mainly refer to single aspects to explain a limited TC on the level of individual countries, but it is not clear how multiple factors impact TC, how TC changed during the pandemic and how TC differs between world regions. Finally, most research thus far has been based on data from high-income countries, and thus, the limitations of TC in resource-limited regions and countries remain poorly understood. Here, we analyse the relationships between TC and vaccination and multiple factors that account for wealth, governance and social inequality and compare them across regions of the world for 2020 and 2021 to account for changes in TC and the advent of COVID-19 vaccination.

METHODS

Data collection

The dataset comprises 109 countries, based on the availability of data for all analysed variables, and is grouped into seven super-regions according to the Global Burden of Disease (GBD) study classification[9] (figure 1A and online supplemental table S1). These super-regions encompass countries that are geographically close, epidemiologically similar and show similar cause-of-death patterns.[9] All the missing data were analysed and taken out before the first analysis, ensuring the most complete dataset possible. Therefore, 73 from the total 193 countries (https://www.un.org/en/about-us/member-states) could not be included, either because they are not part of the GBD regions or due to lack of data, including China, Oman, Venezuela, Cuba, Democratic Republic of the Congo among others (figure 1A and online supplemental table S2). Data on SARS-CoV-2 TC and SARS-CoV-2 vaccination were obtained from Our World in Data (https://github.com/owid/covid-19-data/tree/master/public/data, accessed on 8 February 2022).[1] TC was calculated as the cumulative sum of the maximum total number of tests per 1000 persons per month for the period April 2020 to December 2021 only, since afterwards the TC was too heterogeneous to follow. TC database represents publicly available data published by official sources from the beginning of the pandemic until early 2022, and it is based on molecular testing.[4] Vaccination was calculated as the cumulative sum of applied doses for 2021. Data on the second measles-containing vaccine dose (measles–mumps–rubella (MMR)) by the nationally recommended age were obtained from the WHO 'The Global Health Observatory' data (https://www.who.int/data/gho/data/indicators/indicator-details/GHO/measlescontaining-vaccine-second-dose-(mcv2)-immunization-coverage-by-the-nationally-recommended-age-(-), accessed on 6 June 2023). All count data were rescaled to values per 100 000 to account for differences in the total population. All variables and sources are shown in table 1.

Data analyses

Socioeconomic status (SES) has been identified as a fundamental cause of infectious or non-infectious disease and mortality.[10] Following a preliminary cross-country exploratory analysis of COVID-19 infection and fatality rates,[11] along with a health interview study in the USA suggesting that sociodemographic and economic variables (eg, marginalisation, economic disparities and limited resources) impact COVID-19 testing,[12] we initially evaluated 10 globally available and complete sociodemographic and economic variables related to wealth, governance and social inequality in relation to COVID-19 TC (table 1). To assess which variables to use in the model, we first calculated correlation matrices (Spearman's ρ) for all pairs of dependent and independent variables in the dataset (online supplemental figures S1 and S2). Absolute pairwise correlation coefficients≥0.8 were interpreted as indicating collinearity between independent variables,[13] and therefore, these variables were not used for the analyses. As a result, to avoid multicollinearity, the variables human development index (HDI), gross domestic product (GDP) and averaged aggregated governance index exceeding the threshold were excluded. Therefore, the variables current health expenditure (CHE), urban population (UP), population density (PD), employment-to-population ratio (EP), gender inequality index (GI), Gini index (Gini) and VE met the criteria for additional multivariable analyses (online supplemental figures S3 and S4). For the models and analyses, we applied a logarithmic transformation to the skewed variables, GDP, PD, TC and mortality only. All relevant variables selected based on the correlation coefficients were

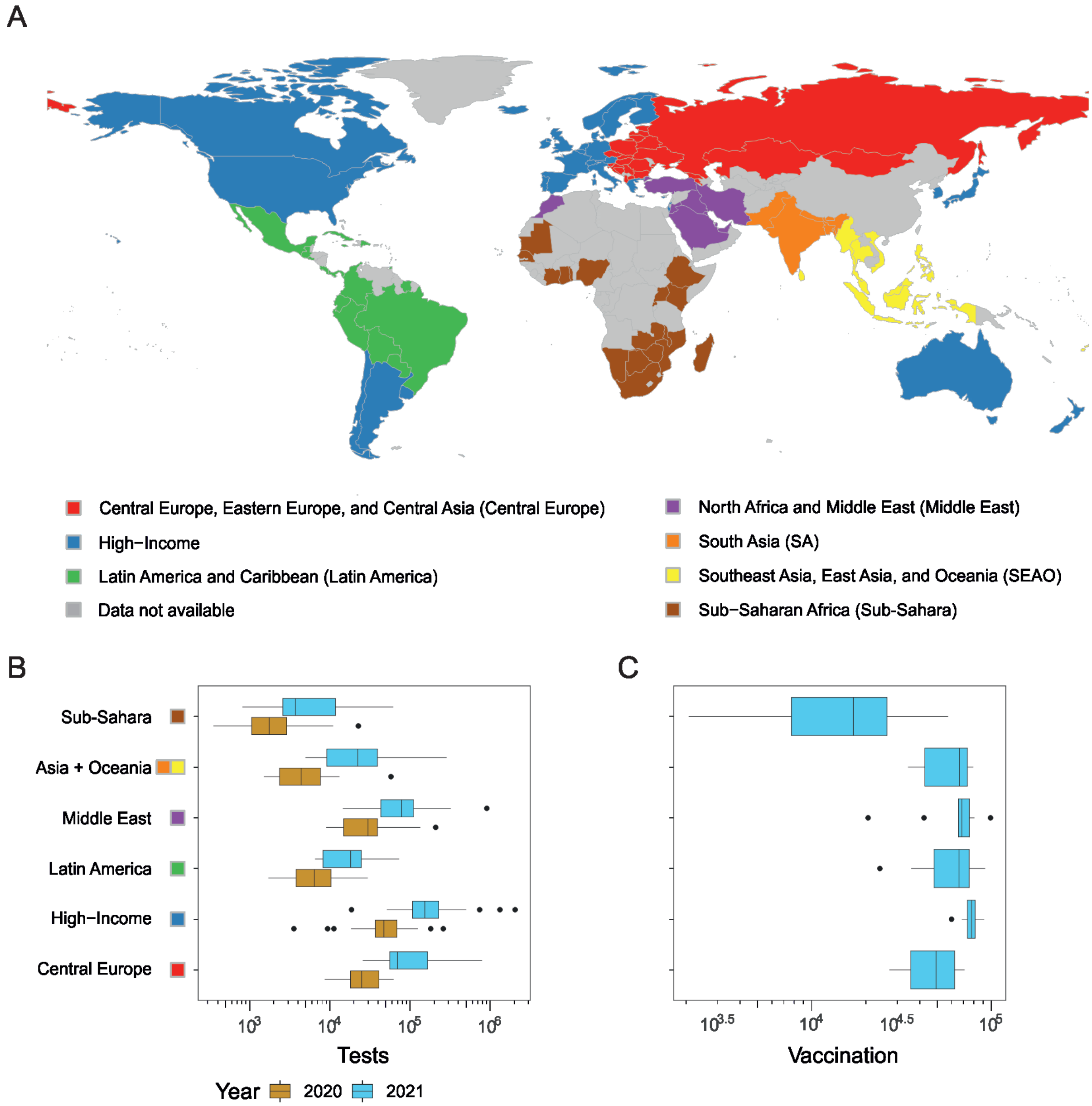

Figure 1 Global burden of disease super-regions (GBDRs) and their testing capacity and vaccination status in 2020 and 2021. (A) Maps of the countries included in this study and grouped according to the GBDRs (map source: https://www.naturalearthdata.com/). The seven GBDRs included Central Europe, Eastern Europe and Central Asia (Central Europe; n=22); North Africa and the Middle East (Middle East; n=10); high-income region (High-Income; n=31); Latin America and the Caribbean (Latin America; n=16); Sub-Saharan Africa (Sub-Saharan; n=18); South Asia (SA; n=4); and Southeast Asia, East Asia and Oceania (SEAO; n=8). As only four SA countries had sufficient data and considering that GBD regions are defined based on epidemiological similarity and geographical closeness, we grouped SA and SEAO together for all subsequent analyses and denoted this as Asia and Oceania. (B) Boxplots of COVID-19 laboratory tests per 1000 inhabitants and (C) COVID-19 vaccination rates in 2021 for the six GBDRs.

assessed descriptively, reporting medians and interquartile ranges (IQRs), stratified by the GBD super-regions.

The effects of sociodemographic and economic variables on TC and COVID-19 vaccination were analysed both globally and within GBD regions, where the ‘high-income’ region was chosen as the reference region due to its high TC. We fitted a negative binomial model, as this generalisation of the Poisson model includes an additional reciprocal dispersion parameter ϕ to account for overdispersed count data. For the global (across GBD regions) analysis, we fit the models with TC and vaccination as the dependent variables and the sociodemographic and economic variables as the independent variables, just as the global region to account for clustering. For the regional analysis, we fit the models separately for each region, using only the seven sociodemographic and economic variables as independent variables. For these analyses, the data were rescaled within each region to assess effects relative to the region-specific mean and variability of the variables

Table 1 List of indices and indicators included in this study

Indicator	Abbreviation	Unit	Year	Source
Wealth				
Human development index	HDI	Value	2019	[35]
Gross domestic product	GDP	US$ per capita	2019	[36]
Current health expenditure	CHE	% of GDP	2017	[11 12]
Inequality				
Gender inequality index	GI	Value	2019	[35]
Gini index	Gini	Value	2019	[35]
Demographic and socioeconomic indicators				
Urban population	UP	%	2019	[35]
Population density	PD	Habitants per square km	2019	[35]
Employment-to-population ratio	EP	%	2019	[35]
Vulnerable employment	VE	% of labour force	2019	[35]
Governance				
Averaged aggregated governance index		Value	2020	[37]
Incidence		COVID-19 cases per 1000 people	2020–2021	[1]
Vaccination		Doses per 1000 people	2021	[1]
Test capacity		Performed tests per 1000 people	2020–2021	[1]

of interest. To investigate differences between COVID-19 vaccines and other established and mandatory vaccines, the same model was also fitted with the absolute number of MMR vaccinations, and the regression coefficients were compared.

The relative change (RC) of the outcome variable in % by socioeconomic variable changes of 1 standard deviation (SD) was derived from the regression coefficient β as $RC=e^{\beta}-1$[14] based on the standardised variables, along with 95% CIs. All analyses were based on complete cases only and performed separately for 2020 and 2021 due to differences in pandemic management and to differentiate the influence of vaccination on TC. The distributions of the residuals of the regression models were inspected visually for adherence to the normality assumption.

All analyses were performed in R V.4.3.1[15] and additional packages.[16–20] We used the 'MASS' package to fit the negative binomial models.[21] The R code is available at https://github.com/drexler-virus-epidemiology/Covid_testing_SE_constraints and all datasets are available online, for their source refer to table 1.

Patient and public involvement

Patients or the public were not involved in the design, or conduct, or reporting, or dissemination plans of our research.

RESULTS

TC constraints across global regions

The median global number of SARS-CoV-2 TC increased 3.4-fold from 2020 to 2021, from 18 051 tests per 100 000 people in 2020 (IQR=37 207) to 61 852 tests per 100 000 people in 2021 (IQR=109 975) (figure 1B). In all seven GBD regions, TC increased by a minimum of 2.1-fold for 'Sub-Sahara' (from a median of 1800–3700 tests) and a maximum of 4.9-fold for 'Asia and Oceania' (from a median of 4500 to 22 000) between 2020 and 2021 (figure 1B and table 2). To establish which socioeconomic variables are associated with TC across global regions, we fitted the model with the global regions as the independent variable, using the entire dataset for each year. After adjustment for the other variables, no other GBD region was able to reach TC levels close to those of the 'high-income' region during either 2020 or 2021 (figure 2A). Although the 95% CIs overlapped between the global regions, the regional RC in TC showed a negative trend in 2021, suggesting that regional constraints hindered TC upscaling in 2021. Specifically, we observed that in the 'Sub-Sahara' and 'Latin America' regions, TC was lower than 'high income' in both 2020 (RC −67%; 95% CI −89% to −6.5% and RC −63%; 95% CI −83% to −17%) and 2021 (RC −92%; 95% CI −98% to −69% and RC −63%; 95% CI −83% to −17%) (figure 2A). For the 'Asia and Oceania' region, TC levels were lower than those of the 'high-income' region during 2021 (RC −68%; 95% CI −89% to −2.8%), suggesting that TC modifications occurred during the second pandemic year, possibly due to the zero COVID-19 strategy in China that was adopted by neighbouring countries during 2020–2021, leading to a decrease in the number of tests performed[22] (figure 2A).

By analysing the factors associated with TC among the socioeconomic variables (figure 2B), we found that VE was

Table 2 Medians and IQRs of the dependent and independent variables used for the models stratified by the global burden of disease subregions

Median (IQR)	High income; n=31	Central Europe; n=22	Sub-Sahara; n=18	Latin America; n=16	Asia and Oceania*; n=12	Middle East; n=10
TC_{2020}	47 000.00 (32 000.00)	25 000.00 (23 000.00)	1800.00 (1900.00)	6500.00 (6600.00)	4500.00 (5600.00)	30 000.00 (1900.00)
TC_{2021}	150 000.00 (120 000.00)	70 000.00 (110 000.00)	3700.00 (9200.00)	18 000.00 (17 000.00)	22 000.00 (30 000.00)	81 000.00 (9200.00)
Vaccination	78 000.00 (7600.00)	49 000.00 (27 000.00)	17 000.00 (19 000.00)	66 000.00 (27 000.00)	67 000.00 (31 000.00)	68 000.00 (19 000.00)
Urban population	85.00 (11.00)	62.00 (12.00)	43.00 (23.00)	58.00 (6.40)	73.00 (20.00)	85.00 (23.00)
Current health expenditure	9.30 (1.60)	6.60 (1.50)	5.20 (2.10)	6.80 (1.20)	3.80 (1.40)	5.00 (2.10)
Employment-to-population ratio	62.00 (4.70)			64.00 (7.70)	61.00 (10.00)	54.00 (20.00)
Vulnerable employment	11.00 (4.60)	14.00 (16.00)	68.00 (24.00)	37.00 (18.00)	51.00 (23.00)	6.10 (24.00)
Population density	2.10 (1.00)	1.90 (0.35)	1.90 (0.55)	1.80 (0.84)	2.40 (0.48)	2.00 (0.55)
Gender inequality index	0.08 (0.05)	0.18 (0.11)	0.53 (0.02)	0.40 (0.06)	0.42 (0.11)	0.28 (0.02)
Gini index	33.00 (5.30)	33.00 (7.80)	43.00 (9.40)	45.00 (3.40)	36.00 (5.60)	37.00 (9.40)

*As only four South Asian countries had sufficient data and considering that global burden of disease regions are defined based on epidemiological similarity and geographical closeness, we grouped South Asia and Southeast Asia, East Asia and Oceania together for all the analyses and denoted this region as Asia and Oceania.
IQR, interquartile range; TC, testing capacity.

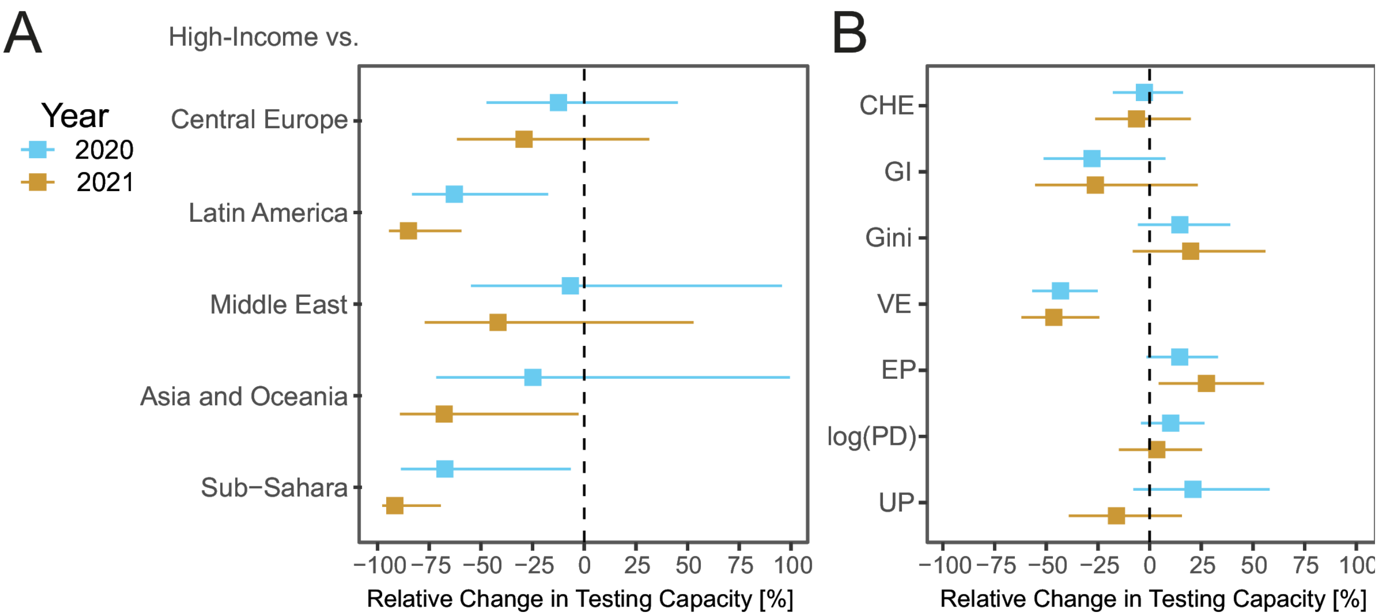

Figure 2 Global regression analysis of the regional relative changes in testing capacity (TC) in 2020 and 2021. (A) Relative change in TC per 1 SD increase in socioeconomic variables is derived from a negative binomial regression model, along with 95% CI. Regional effects were calculated as categorical effects, with the reference region set as 'high income'. (B) Effects of seven socioeconomic variables analysed. CHE, current health expenditure; EP, employment-to-population ratio; GI; gender inequality index; Gini, Gini index; Log(PD), logarithm population density; SD, standard deviation; UP, urban population; VE, vulnerable employment.

associated with reduced TC both in 2020 (RC −43%; 95% CI −57% to −25%) and 2021 (RC −46%; 95% CI −62% to −24%) (figure 2B). Conversely, EP had a positive effect on TC in 2021 (RC 27%; 95% CI 44% to 55%). Therefore, our analyses might suggest that employment or lack thereof influences changes in TC globally. The remaining variables had no significant effect on TC, as illustrated by the 95% CI overlapping with zero RC (figure 2B).

Associations of COVID-19 and MMR vaccination rates with socioeconomic variables

During the COVID-19 pandemic in 2021, vaccination coverage for key WHO immunisation programme vaccines, including MRR, diphtheria–tetanus–pertussis and polio, fell to decades-long lows but still exceeded 80% globally for the first dose.[23] Conversely, COVID-19 vaccine coverage increased unevenly across regions due to its unequal distribution. Therefore, we compared the effects of region and seven socioeconomic variables on COVID-19 and MMR vaccination rates in 2021 as a reference. We found that compared with high-income countries, countries in Central/Eastern Europe and Central Asia had lower COVID-19 vaccination rates, independent of the other parameters, whereas they had higher MMR rates. The opposite is observed for the Latin American and Caribbean regions, which had lower MMR rates but higher COVID-19 rates than did high-income countries. The differences between the other regions and the high-income region were the same for both vaccines (figure 3A). Regarding the association of the other independent variables with vaccination, all the associations were estimated with rather high imprecision, and interpretation should therefore be treated with caution. However, we observed similar effects of CHE, GI, Gini and VE on both vaccination regimens, indicating that the directions of the effects of these variables are the same for both vaccine types. Interestingly, greater gender inequality was negatively associated with both vaccines, yet the association was more pronounced for the COVID-19 vaccine. This association between the independent variable and vaccination differed for the other parameters, for example, for UP, in particular, we observed that in countries with a greater UP, the rate of COVID-19 vaccination increased, while the rate of MMR vaccination decreased (figure 3B and online supplemental table S3).

For MMR vaccination, the independent variables were not significantly associated with an RC in vaccination, exemplified by the close to 6 billion vaccine doses in Asia at the end of 2021 and lagging in the 'Sub-Sahara' region, reaching close to 300 million at the end of 2021, 130% of the population in 'Asia and Oceania', and 20% in the 'Sub-Sahara' region.[1] However, for both COVID-19 and MMR, CHE, GI, Gini and VE showed similar distributions of RC, indicating that these socioeconomic variables may influence both vaccines similarly. In contrast, EP, logarithm population density (Log(PD)) and UP showed differing patterns, possibly due to lower MMR vaccine coverage in rural areas, which was less evident during the COVID-19 vaccine rollout (figure 3 and online supplemental table S3).

Region-specific trends affecting TC

The analysis of RCs in TC between global regions is crucial for comparing areas with similar resources and

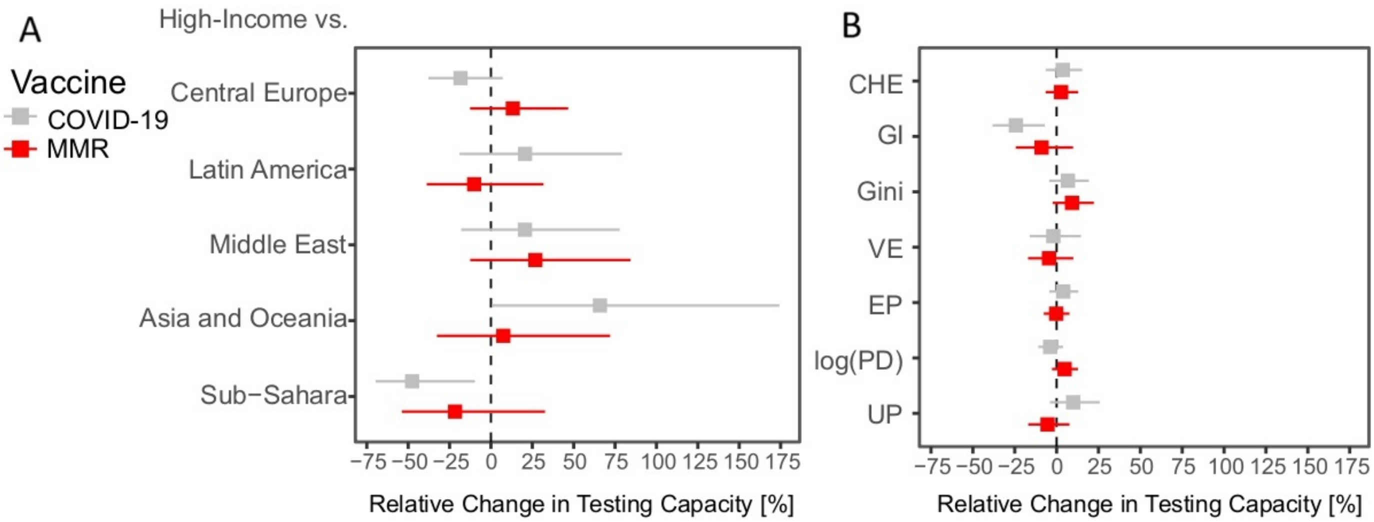

Figure 3 Global regression analysis of the regional relative change in vaccination rate of COVID-19 and measles–mumps–rubella (MMR) in 2021. Regression coefficients and 95% CI are given as relative change in vaccination per change in predictor SD by ±1. (A) Regional effects calculated as categorical effects with the reference region set as 'high income' (GBDR7). (B) The effects of seven variables analysed as joint predictors. CHE, current health expenditure; EP, employment-to-population ratio; GI; gender inequality index; Gini, Gini index; Log(PD), logarithm population density; SD, standard deviation; UP, urban population; VE, vulnerable employment.

infrastructure, as well as similar disease patterns and risk factors.[24] However, there is also considerable variation within regions, as exemplified by the outliers in TC (figure 1B). The regression analysis results are reported in online supplemental tables S4 and S5, and the estimates of the regression coefficients are shown as RCs in figure 4A–F. Region-level analyses revealed stark heterogeneity in the associations between socioeconomic variables and TC between the analysed years (2020 vs 2021) and across regions. CHE was positively associated with TC in both 'Latin America' and 'Asia and Oceania' and negatively associated with TC in the 'high-income' region. In 'Asia and Oceania', CHE was highly positively associated with TC in both 2020 (RC_{2020} 199%; 95% CI 74% to 405%) and 2021 (RC_{2021} 142%; 95% CI 67% to 24%) (figure 4A,E). Some associations can be attributed to the Maldives, which had the highest TC (TC_{2020} 57, 871; TC_{2021} 287, 038) and CHE (CHE=9.03%) in the region. Similarly, the negative trend of CHE in the 'high-income' region may be mostly driven by the USA, with the global maximum CHE (CHE=17.1%) but being the country with the 9th and 27th (out of 109) highest TC in 2020 and 2021, respectively (figure 4A). The region 'Latin America' showed an observable trend in CHE in 2020 (RC_{2020} 68%; 95% CI 12% to 160%) that was lower in 2021 (RC_{2021} 32%; 95% CI −12% to 100%) (figure 4C). This observation might be indicative of the initially limited supply and access of low-income and middle-income countries to material to build up TC, requiring country-level analyses. In sum, CHE seems to be associated with TC in most countries. However, for 'high-income' countries, divergent pandemic management not focused on testing but on vaccine development and medical treatments might have led to the negative effects observed.

VE was associated with decreased TC in both the 'high-income' and 'Central Europe' regions (figure 4A, B, F). This effect was greater in 2020 than in 2021, suggesting that in those regions, TCs could not reach larger populations with VE in 2021. EP had a negative effect on TC in the 'Middle East' ($RC_{2020–2021}$ −56%, −89%; 95% CI −38% to −95%), 'Asia and Oceania' (RC_{2021} −52%; 95% CI −33% to −66%) and 'high-income' regions ($RC_{2020-2021}$ −7%, −13%; 95% CI −33% to 32%) and a consistently positive effect in 'Central Europe' (RC_{2020} 29%; 95% CI 5.3% to 60%) and 'Latin America' regions ($RC_{2020-2021}$ 42%, 65%; 95% CI −19% to 200%), suggesting that more economically resourceful regions with a high employment ratio might have enough acquisitive power to increase TC and vice versa (figure 4). Finally, variables associated with economic inequality (Gini, GI, EP) were associated with a relatively decreased TC in the 'Middle East' and 'Asia and Oceania' regions (RC shown in figure 4).

We additionally analysed region by region to assess if the combination of independent variables might lead to insights into how TC was associated to the socioeconomic factors. For the 'high-income' region (figure 4A), the combination of negative trends in VE_{2020}, UP_{2021} and $CHE_{2020–2021}$, suggests diversity in pandemic management, affecting TC. This could be due to varying healthcare expenditures and UP distributions. For 'Central Europe' (figure 4B), a negative trend in VE_{2020}, but a positive effect in $Gini_{2021}$ and EP_{2020}, suggests that employment played an important role on TC within these countries, and even though there was VE, improvements in income equality and employment rates may have positively influenced TC. For 'Latin America' (figure 4C), a positive trend in $Log(PD)_{2020}$ and CHE_{2020}, indicates that living in city centres and health expenditure increased TC, but that

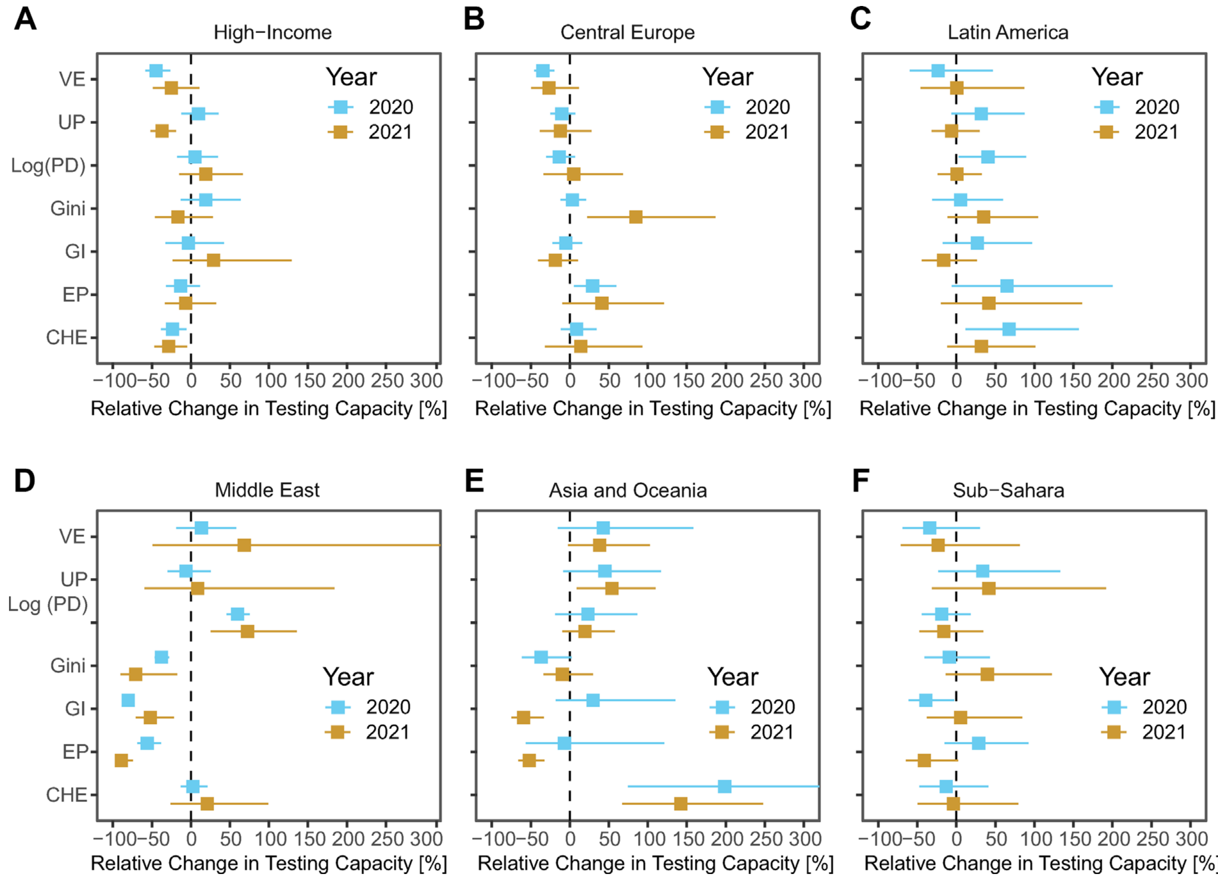

Figure 4 Estimates of the associations between socioeconomic and population composition factors and national COVID-19 testing capacity (TC) within global burden of disease regions. Estimates were derived based on regional negative binomial regression models stratified by 2020 and 2021. Regression coefficients and 95% CI are given as relative changes in TC per change in the socioeconomic variable SD by +1. (A) High-income region. (B) Central Europe region. (C) Latin American region. (D) Middle East region. (E) Asia and Oceania region. (F) Sub-Saharan region. CHE, current health expenditure; EP, employment-to-population ratio; GI; gender inequality index; Gini, Gini index; PD, population density; SD, standard deviation; UP, urban population; VE, vulnerable employment.

effects were short-lived due to economic and political instabilities. For 'Middle East' (figure 4D), a positive trend on $Log(PD)_{2020–2021}$, and negative in $Gini_{2020–2021}$, $GI_{2020–2021}$, $EP_{2020–2021}$, suggests income and gender inequality, and employment issues could have hampered TC. For 'Asia and Oceania' (figure 4E) a positive effect on $CHE_{2020–2021}$, and a negative in GI_{2021}, $Gini_{2020}$ and EP_{2021}, suggests resource allocation for testing was crucial during pandemic management, but gender inequality and employment issues might have modified TC. Finally, a negative effect on $GI_{2020\ in}$ 'Sub-Sahara' (figure 4F) indicates gender inequality issues that hampered broad access to testing. In sum, health expenditure, gender inequality, employment vulnerabilities and access to employment may be common denominators limiting countries' efforts to increase TC (figure 4).

DISCUSSION

Our study suggests that socioeconomic disparities and gender inequality might modify TC globally and regionally. Global studies that have evaluated sociodemographic and economic variables in relation to COVID-19 incidence and mortality[11] have shown that GDP per capita explains most of the variation in the COVID-19 infection rate. However, regional health interview studies showed that the decision to undergo testing is influenced by education level and SES.[12] Our results reveal that globally, TC was lower with increased VE, beyond GDP alone. This applies especially to the 'high-income' and 'Central Europe' regions, in line with studies showing that under conditions of occupational vulnerability, quarantine measures can hardly be carried out, and the decision to be tested is affected, leading to ineffective contact tracing.[12] Therefore, there is significant diversity in terms of the effects of pandemic management on TC, mainly due to varying healthcare expenditures and UP distributions in Europe and North America, in concordance to the health-interview study.[12] The global impact of VE underscores the necessity of ensuring adequate working conditions, which might lead to the equitable provision of health services. This is particularly true in high migration settings, such as in Venezuela[25] and Haiti,[26] given the humanitarian, political and environmental challenges to local economies and health systems, leading to discrimination.[27]

We also observed gender inequality in relationship to TC in the 'Middle East', potentially due to women's limited access to health services. This finding is consistent with the global detrimental trend of higher gender inequality on COVID-19 vaccination rates in 2021, supported by studies showing how gender disparities in vaccination coverage in Bangladesh and Nepal increase with poverty, lower maternal education and lack of female autonomy.[28–30] Ensuring access to basic monitoring systems, for example, access to prenatal and postnatal services for pregnant women in Asia or the Middle East, could enable equal access, acceptance and effectiveness of testing for COVID-19 or other emerging pathogens.

Our study revealed that TC in Asia and Latin America was associated with investment in public health, which might have affected the provision and equitable access to adequate health services. However, the complexity of the Latin American region substantiated how TC was also affected by the structure of health systems,[31] by the coordination between these and health authorities and by misinformation policies.[32] Therefore, in Latin America, living in city centres and increasing health expenditures were associated with increased TC, but these effects lasted only months likely due to economic and political instability.

Compared with 'high-income' countries, 'Sub-Sahara' showed an effect of a constrained COVID-19 vaccination rate in 2021. This highlights the importance of increased attention from global actors in Africa during the pandemic, for example, through the COVAX initiative for equitable distribution of vaccines.[28]

Our study was limited by data availability mostly from resource-limited settings, known to have reporting limitations, the heterogeneous nature of the data and the number of countries within GBD regions.[33] Data acquisition for future pandemics should be a crucial strategy to be implemented, using open source, safe, reliable and real-time databases to accurately calculate public health estimates. The indices are based on available data, but potential gaps, especially from low-resource settings, may impact their robustness despite efforts to address limitations. Factors studied here might not be enough to capture all socioeconomic aspects by which the regions differ. Additional factors such as discrimination, racism and inequality within regions might also play a role in ensuring the equitable supply and distribution of diagnostic materials.[2] Additionally, endemic corruption in Latin America might have also affected our analyses due to a decline in health expenditure; however, research has shown no evidence of a link between corruption and the COVID-19 public health response.[34] The high correlation between socioeconomic variables, especially between GI, HDI and GDP, limits the scale to which effects can be attributed to a single variable and needs to be interpreted accordingly. Additionally, some analyses have shown contradictory values. These differences might be caused by the divergent individual datasets underlying the aggregated factors.

Despite these limitations, our study highlights the importance of understanding the drivers of TC, which is crucial for accurate estimates of incidence and mortality, enabling informed epidemiological studies and effective public health measures. The lack of testing exacerbates other factors, such as policy incoherence in coordinating public responses to the pandemic, underestimation of the risks associated with SARS-CoV-2 infection due to lack of information, and limited quality of health services due to funding gaps, leading to a delay in control measures and increased incidence and mortality, particularly in low-income and middle-income regions.[8] Socioeconomic inequalities can exacerbate health inequalities, jeopardise the effectiveness of public health policies and jointly prevent a globally coordinated response to pandemics.

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