INTERNATIONAL MONETARY FUND

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WP/21/247

[2021]
[OCT]

WORKING PAPER

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Abstract

This paper examines empirically the determinants of COVID-19 vaccine rollouts and their effects on health outcomes. We assemble a comprehensive and novel cross-country database at a daily frequency on vaccinations and various health outcomes (new COVID-19 cases, fatalities, intensive care unit (ICU) admissions) for the period December 16, 2020-June 20, 2021. Using this data, we find that: (i) early vaccine procurement, domestic production of vaccines, the severity of the pandemic, a country's health infrastructure, and vaccine acceptance are significant determinants of the speed of vaccination rollouts; (ii) vaccine deployment significantly reduces new COVID-19 infections, Intensive Care Unit (ICU) admissions, and fatalities, and is more effective when coupled with stringent containment measures, or when a country is experiencing a large outbreak; and (iii) COVID-19 cases in neighboring countries can lead to an increase in a country's domestic caseload, and hamper efforts in taming its own local outbreak.

ISBN	978-1-58906-315-0 (Paper) 978-1-58906-634-2 (ePub) 978-1-58906-683-0 (PDF)
JEL Classification Numbers:	C31; C33, E65, O50, F4.
Keywords:	COVID-19; pandemics; vaccinations; containment measures.
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I. Introduction

Vaccination against the coronavirus disease (SARS-nCOV-2) is understood to be the a key way out of the COVID-19 pandemic and the economic crisis it has brought about. However, access to and uptake of COVID-19 vaccines has been heterogeneous and uneven, despite the recent pickup as vaccine availability has improved. Countries in North America and Europe started vaccinations earlier on and are further along than other regions such as Africa and the Middle East. Vaccinations in Asia started later but have picked up recently (Figure 1). Across income groups, advanced economies have vaccinated a much larger share of their populations than emerging and developing economies, on average (see Annex Figure 1).

The epidemiological literature has documented the effectiveness of vaccines on COVID-19 health outcomes thus far for individual countries or a small set of two to four countries (see literature review below), but there is little cross-country evidence on the determinants of COVID-19 vaccine rollouts and their impacts on health outcomes. This paper adds to the existing literature by: (i) empirically assessing the determinants and drivers of vaccine rollouts across countries; (ii) analyzing the health impact of vaccinations at the country level for an extensive sample of 126 advanced and developing countries; (iii) studying the role of country-specific conditions—such as containment measures. the severity of the COVID-19 outbreak, the dominant COVID-19 variant, or the type (mRNA vs non-mRNA) of vaccine used —in amplifying/dampening the effect of vaccinations; and (iv) examining the health spillover effects of COVID-19 cases in neighboring countries.

For this purpose, we put together a database of daily data on vaccinations (first and second doses) per capita, confirmed COVID-19 infections, deaths, intensive care units (ICU) admissions of COVID-19 patients, nonpharmaceutical interventions (henceforth known as

containment measures), procurements of vaccines, vaccine acceptance proxies, vaccine production and various metric of health infrastructure and mobility indices for a broad range of countries, spanning from December 16th 2020 to June 20th 2021.

Our results suggest that both supply and demand side factors are important determinants of vaccine rollout. On the supply side, early procurement, domestic production of vaccines, and countries' health infrastructure are important determinants of the speed of rollout in a given country. On the demand side, the largest impact on the pace of vaccinations comes from the severity of the pandemic in a given country during the first COVID-19 wave, while the willingness of the population to accept the vaccine also contributes to a more rapid pace of vaccination in a country.

Turning to the effects of COVID-19 vaccines on health outcomes, we find that vaccinations have a large and statistically significant effect on new COVID-19 cases, Intensive Care Unit (ICU) admissions and ultimately deaths (as a share of population), as well as the reproduction rate of the virus. Vaccinations also reduce the number of ICU patients per infected person, thereby enhancing the health system's resilience to cope with the spread of the virus. In addition, we find that the effect of COVID-19 vaccines varies depending on country-specific conditions. COVID-19 vaccines are more effective in reducing new COVID-19 infections when combined with stringent containment measures, suggesting complementarity between vaccines and containment policies. Furthermore, an increase in vaccine rollouts is more likely to lead to a larger decline in new cases if a country is in the middle of a significant outbreak, suggesting that vaccines should be channeled where possible, to countries facing more acute outbreaks. On the other hand, while the data is still emerging, we find early evidence consistent with epidemiological studies that suggests that the presence of more infectious variations of COVID-

19, such as the Delta variant, makes vaccines less effective. Similarly, tentative results based on the share of mRNA vaccines relative to non-mRNA vaccines suggests that mRNA vaccines have a greater marginal impact relative to their non-mRNA counterparts, consistent with the findings of the epidemiological literature.

Finally, we also find evidence for significant health spillovers, with higher COVID-19 cases in neighboring countries being associated with higher cases domestically. In conjunction with the result that vaccines provide larger health gains in countries with severe outbreaks (or conversely that there are diminishing returns to vaccine rollout in countries with limited COVID cases), this highlights the potential gains from vaccine sharing.

Our paper contributes to two strands of the literature. The first is the one that looks at the role of supply and demand side factors which may impede or accelerate the rollout (and uptake) of vaccines, including COVID-19 vaccines. Figueiredo et al. (2020) conduct the largest country study to date of global vaccine confidence across 149 countries and find that confidence in the importance of vaccines (rather than their safety or effectiveness) has the strongest association with vaccine uptake compared to other determinants considered. Malik et al. (2020) study the determinants of COVID-19 vaccine acceptance in the US in May 2020, and find an average 67 percent acceptance rate, which is higher among males (compared to females), older adults (compared to younger adults), and college or graduate degree holders (compared to people with less than a college degree). Goel and Nelson (2021) also look at the drivers of vaccine administration and delivery efficiency for 50 US states and find factors such as more COVID-19 deaths, demographics, and health infrastructure play an important role. Dabla-Norris et al. (2021) use survey data for 17 countries to examine the drivers of COVID-19 vaccine demand and find that vaccine hesitancy as a significant deterrent for vaccine uptake, and concerns over the

severity of COVID-19 or trust in government as drivers of vaccine demand. This paper adds to this growing literature on the determinants of COVID-19 vaccines by examining the role of demand and supply side factors in explaining rollouts across a sample of nearly 200 countries.

The paper also contributes to a second strand of the literature examining the health effects of COVID-19 vaccines. Dagan et al. (2021) find an efficacy rate for BNT162b2 (Pfizer-BioNTech) mRNA-based COVID-19 vaccines of 46 percent (21 days after receiving the first dose) and 92 percent (7 days after receiving the second dose) in preventing infections, hospitalizations, severe diseases, and deaths in Israel for a range of outcomes across diverse populations in a noncontrolled setting. Using data for healthcare workers in the UK, Hall et. al. (2021) estimate vaccine effectiveness against infection for the BNT162b2 vaccine to be 70 percent (21 days after the first dose), increasing to 85 percent (7 days after the second dose). Bernal et al. (2021) find similar results for BNT162b2 and also document that with ChAdOx1-S (Oxford-AstraZeneca) non-mRNA vaccine, effects were seen from 14 to 20 days after vaccination, reaching an effectiveness of 60 percent from 28 to 34 days, increasing to 73 percent from day 35 onwards. Polack et al. (2020) find a 95 percent efficacy in preventing SARS-Cov-2 infections seven days after the second dose of the BTN162b2 mRNA-based vaccine in randomized trials of a large sample size pooled from within the US, Argentina, Brazil and South Africa. Deb et al.(2021a) uses a cross-country regional database of 17 countries (326 regions) to analyze the effects of COVID-19 vaccines on health outcomes. They find that a 10 percent increase in the share of the population with one vaccine dose (comparable to moving from a region which has started vaccinations and is at the 25th percentile distribution to a region at the 75th percentile distribution) reduces infections after 21 days by 0.10 percentage point. This paper contributes to this strand of the literature by extending on Deb at al. (2021a) to examine the

health outcomes of COVID-19 vaccines across a much larger sample of 126 countries, explore the role of country-specific conditions in shaping the effect of COVID-19 vaccines, and the effect of the COVID-19 pandemic in neighboring countries on the country's caseload.

The paper is structured as follows. Section II describes the data and Section III the methodological approach. Section IV discusses the results on vaccine rollouts, while section V the results on effects of vaccinations on health outcomes, the role of country-specific factors, robustness checks, and the effects of neighboring pandemics on a country's own COVID-19 caseload. The last section concludes.

II. Data

Our empirical analysis relies on the assembly of a comprehensive country-level database of daily COVID-19 cases, ICU admissions, vaccinations and deaths; mobility indicators, government responses to the pandemic, public opinion and country-specific characteristics. Annex table A1 provides further details on the data.

COVID-19 related variables

COVID-19 cases and fatalities. Daily data on COVID-19 cases and fatalities are collected from the COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University.[1] Coverage begins from January 22, 2020 for 208 countries.

COVID-19 vaccines and ICU admissions are sourced from the Our World in Data COVID-19 repository.[2] Vaccinations data is disaggregated by first and second shots, with data covering up

[1] https://github.com/CSSEGISandData/COVID-19
[2] https://covid.ourworldindata.org/

to 202 countries starting in December 2020. Data starts from January 1st, 2020 covering 23 countries for intensive care admissions.

COVID-19 variants. We collect data from CoVariants which provides a weekly overview of 19 SARS-CoV-2 variants for 85 countries starting in the last week of April 2020.[3] The dataset reports the share of a particular variant amongst all samples sequenced in a country for a given week.

Vaccine type. Data on administered vaccine is available for 14 brands (2 of which are mRNA, Pfizer and Moderna) in 156 countries from Airfinity.[4] We construct a variable that captures the share of mRNA vaccines as of June 20, 2021.

Vaccine production location. Airfinity provides data on vaccine production location for 15 countries starting on November 19th, 2020.[5] We use this to create a dummy variable if a country is producer of a COVID-19 vaccine.

Government Responses

Vaccine procurement deals. We use data on vaccine procurement from the Duke Global Health Innovation Center.[6] The daily data includes confirmed doses (deals that have been signed and finalized) and potential doses (deals that are under negotiation or additional doses for existing deals), covering 102 countries starting on May 01, 2020. We also use procurement and supply data from Airfinity to check the robustness of our results.[7]

[3] https://covariants.org/
[4] https://www.airfinity.com/
[5] https://www.airfinity.com/. All EU countries are considered to be producers as these countries have a vaccine sharing arrangement.
[6] https://launchandscalefaster.org/covid-19
[7] https://www.airfinity.com/

Stringency of containment measures. For containment measures indices, we use data from Oxford's COVID-19 Government Response Tracker (OxCGRT).[8] OxCGRT collects information on government policy responses across eight dimensions, namely: (i) school closures; (ii) workplace closures; (iii) public event cancellations; (iv) gathering restrictions; (v) public transportation closures; (vi) stay-at-home orders; (vii) restrictions on internal movement; and (viii) international travel bans. The database scores the stringency of each measure ordinally, for example, depending on whether the measure is a recommendation or a requirement and whether it is targeted or nation-wide. We normalize each measure to range between 0 and 1 to make them comparable. In addition, we compute and aggregate a Stringency Index as the average of the sub-indices, again normalized to range between 0 and 1. The data starts on January 1, 2020 and cover 151 countries/regions.

Mobility Indicators

Retail Mobility. Data on retail and recreation mobility is collected from Google Mobility Reports.[9] The reports provide daily data by country and highlight the percent change in visits to places related to retail and recreation activity (e.g., restaurants, cafes, shopping centers, movie theaters, museums, and libraries). The data is reported as the change relative to a baseline value for that corresponding day of the week, the baseline is calculated as the median value for that corresponding day of the week, during the 5-week period between January 3rd and February 6th, 2020. Daily data are available for 135 countries in our dataset, with coverage beginning from February 15, 2020.

[8] https://covidtracker.bsg.ox.ac.uk/
[9] https://www.google.com/covid19/mobility/index.html

Public Opinion Proxies

Vaccine acceptance. Data on vaccine acceptance is collected from The University of Maryland Social Data Science Center Global COVID-19 Trends and Impact Survey based on a representative sample of over 200,000 daily responses of Facebook users who are invited to report on topics including, for example, symptoms, social distancing behavior and vaccine acceptance. Weights are assigned to reduce nonresponse and coverage bias.[10] Our sample covers 100 countries starting on December 21st, 2020.

Attitude towards authorities. We capture the attitude of the population towards authorities, and by extension, towards the vaccination campaigns by using proxies for trust in government available form the World Economic Forum and political stability from the World Bank.

Country-Specific Characteristics

Health infrastructure. We use two sources to measure a country's health preparedness and competitiveness. First, Health Index data from the WEF's 2019 Global Competitiveness Report is obtained. This index measures the health status of the population, their link to productivity and the quantity and quality of the basic education received for 137 countries. Secondly, we collect data from the 2019 Global Health Security (GHS) Index which is the first comprehensive assessment and benchmarking of health security and related capabilities across 195 countries.[11] The GHS Index seeks to illuminate preparedness and capacity gaps to increase both political will and financing to fill them at the national and international levels. In addition, to measuring

[10] https://covidmap.umd.edu/api.html
[11] https://www.ghsindex.org/

countries health infrastructure, we use hospital beds and physicians per 1,000 people at the country level from the World Bank DataBank.[12]

Geographical distances between each country and the rest of the world capitals is obtained from the CEPII GeoDist Database which incorporates country-specific geographical variables for 225 countries in the world.[13]

III. Methodology

This section lays out the methodology used to assess: (i) the determinants of vaccine rollouts; (ii) the impact of vaccine on health outcomes; (iii) the heterogeneity in the impact of vaccines depending on country conditions, COVID-19 variant, and type of vaccine; and (iv) the adverse health spillovers from increased infections in neighbors.

A. Determinants of vaccine rollouts

We exploit cross sectional variation in vaccination rollout across countries to assess the role of demand and supply side factors. The cross-sectional setting allows us to explore the role of time invariant factors in explaining vaccine rollout, as well as factors captured at a particular point of time—for example the scale of the pandemic before the vaccination rollout that may have affected attitude of authorities and the population towards vaccines; or procurement of vaccines early in the year which affected supply later during the rollout phase. We begin by using univariate regressions to look at how total vaccinations to-date are correlated with various factors such as vaccine procurement in January 2021, severity of the pandemic in the country,

[12] https://data.worldbank.org/
[13] http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele.asp

etc. Using the results from these univariate regressions, we select the most significant indicators from each category and try to explain how much of the overall heterogeneity in vaccine rollout is explained by these factors considered together. Specifically, we estimate the following equation:

$$V_i = \alpha + \beta Proc_i + \gamma Health_i + \delta Cases_i + \theta Accept_i + \varepsilon_{i,t} \quad (1)$$

where i is an index for country, V_i is the level of vaccination as a share of population as of June 20, 2021 (or the average daily vaccinations since the start of the vaccination campaign), $Proc_i$ is the number of doses procured or being negotiated as a share of population as of January 2021, $Cases_i$ measures the magnitude of the COVID-19 pandemic in the country in question at the end of 2020, and $Accept_i$ captures the attitude of the population towards vaccination at the start of the campaign in January 2021. Equation (1) is estimated with OLS with robust standard errors to account for heteroskedasticity.

B. Baseline effect of vaccinations on health outcomes

For the analysis of the health impact of vaccinations, we move to a country-time panel dataset at the daily frequency that allows for high frequency identification of the impact of vaccinations on health outcomes. Establishing causality is difficult because vaccine rollout may depend on the current and expected evolution of the virus. We try to mitigate reverse causality by allowing for the several lags in the response of new COVID-19 cases/deaths or the reproduction rate to vaccines, and by also controlling for lags in the change of the number of infected cases (deaths and ICU cases). We also control for country fixed effects which at daily frequency effectively controls for vaccine procurement as well as structural factors (such as health capacity) affecting the speed of vaccine rollout. To further account for expectations about the country-specific evolution of the pandemic, we also control for a set of variables which may

affect future infections such as mobility, non-pharmaceutical interventions (NPIs)—including containment measures, enhanced testing, contact tracing and public information campaigns aimed at increasing social awareness—and country-specific time trends.[14] Finally, we also include time fixed effects to account for global factors affecting the evolution of the virus (such as new variants) and vaccination (supply disruptions). In particular, the following specification is estimated:

$$\Delta C_{i,t} = \mu_i + \gamma_t + \beta V_{i,t-l} + \partial X_{i,t-l} + \varepsilon_{i,t} \quad (2)$$

where $C_{i,t}$ alternatively denotes: the cumulative number of COVID-19 cases or deaths as a share of the population, the number of COVID-19 ICU patients as a share of the population or a share of cases (lagged by 21 days), and the COVID-19 reproduction rate—the expected number of secondary cases generated by an index patient—of a country *i* at time *t*.[15] The reproduction rate is estimated using the number of new infections per currently infected individual, multiplied by the duration of illness (see Xu et al 2020).[16] $V_{i,t-l}$ denotes the share of the individuals in the population which have received at least one vaccine shot. μ_i and γ_t are country and time fixed effects. X is a vector of control variables which includes the lagged level of cases as well as the stringency of containment measures index and mobility indices at lag *t-l*, as well as country-

[14] It can be argued that controlling for NPIs may bias the results downwards if NPIs are affected by vaccinations. While we are primarily interested in the partial effect of vaccinations after controlling for NPIs, our results continue to hold if we exclude NPIs as controls.

[15] We do not include other control variables $X_{i,t-l}$ when ICU patients as a share of lagged cases is the dependent variable, as containment measures, mobility and other controls are only expected to impact the absolute level of health outcomes, not the share of cases requiring ICU admission.

[16] The effective reproduction rate can be approximated based on the number of new infections per currently infected individual, multiplied by the duration of illness. Actual new infections on any day are not directly observable, but an unbiased estimator can be obtained by using lags of actual new infections, with the number of lags corresponding to the estimated incubation period of COVID-19, adjusted for delays between the onset of symptoms and testing and recording of a case. For the baseline, we use 7 days of lag, but the results are similar with 10, 14 and 21 days and are available upon request.

specific time trends. ℓ denotes the lags in the response of new COVID-19 cases/deaths or the reproduction rate to vaccines depending on specification. We follow the literature on vaccinations (Deb et al. 2021, Dagan et al. 2021; Logunov et al. 2021; Polack et al. 2021) and opt for 21-day lags as a baseline to allow for delays in the development of immunity but examine various lags as a robustness check subsequently. For deaths, we use a longer lag structure of 42 days to account for the delay with which infections turn into fatalities.

C. Role of country-specific conditions on vaccine effectiveness

Next, we test the role of country-specific conditions in shaping the effects of vaccinations. In particular, we explore whether the impact of vaccines on health outcomes depends on factors such as the stringency of containment measures, the severity of the outbreak itself, the variant of COVID-19 in circulation, or the type of vaccine used. We start off with linear interactions (or a dummy) to assess the role of different country specific factors. In particular, we estimate:

$$\Delta C_{i,t} = \mu_i + \gamma_t + \beta V_{i,t-l} + \vartheta I_{i,t-l} * V_{i,t-l} + \partial X_{i,t-l} + \varepsilon_{i,t} \quad (3)$$

where $I_{i,t}$ denotes alternatively stringency of containment measures, or the level of new COVID-19 cases in a country, share of Delta variant in the country or the share of mRNA vaccines. Equation (3) imposes that the effect of vaccines on cases varies linearly with the interacting variable *I*. We relax this assumption using two alternative specifications. First, we use the smooth transition autoregressive model developed by Granger and Terävistra (1993) to directly test of whether the effect of vaccinations varies across different country-specific "regimes". This allows the effect of vaccines to vary smoothly across regimes by considering a continuum of states, thus making the functions more stable and precise. Specifically, we estimate:

$$\Delta C_{i,t} = \mu_i + \gamma_t + \theta^L F(z_{i,t}) * V_{i,t-l} + \theta^H (1 - F(z_{i,t})) * V_{i,t-l} + \partial X_{i,t-l} + \varepsilon_{i,t}$$

$$\text{with } F(z_{it}) = exp^{-\gamma z_{it}}/(1 + exp^{-z_{it}}) \quad (4)$$

where z is a country-specific characteristic normalized to have zero mean and a unit variance. The weights assigned to each regime vary between 0 and 1 according to the weighting function $F(.)$, so that $F(z_{it})$ can be interpreted as the probability of being in a given regime. The coefficients θ_h^L and θ_h^H capture the impact of vaccinations in cases of very low levels of z ($F(z_{it}) \approx 1$ when z goes to minus infinity) and very high levels of z ($1 - F(z_{it}) \approx 1$ when z goes to plus infinity), respectively.

Second, we use a semi-parametric approach in which we interact vaccinations per capita with quartiles ("bins") of country-specific conditions. This approach allows us to flexibly explore variation in vaccine effectiveness across the distribution of country conditions. We augment equation (2) with the following:

$$\Delta C_{i,t} = \mu_i + \gamma_t + \beta_1 Q_1 * V_{i,t-l} + \beta_2 Q_2 * V_{i,t-l} + \beta_3 Q_3 * V_{i,t-l} + \beta_4 Q_4 * V_{i,t-l} + \sum_{j=1}^{4} \varphi_j Q_j + \partial X_{i,t-l} + \varepsilon_{i,t} \quad (5)$$

where Q_1, Q_2, Q_3, and Q_4 are dummy variables that denote alternatively quartiles of the stringency of containment measures, the level of new COVID-19 cases in a country, the variant of COVID-19 in circulation, or the type of vaccine used. Quartiles are interacted with the percent of the population that has received at least one dose of the vaccine. Interaction terms are also lagged 21 days, consistent with the vaccine variable. If the coefficients on the interaction terms of higher quartiles differ from those at lower quartiles, it signifies that the effectiveness of vaccines depends on country-specific conditions.

D. Effect of COVID-19 cases in neighboring countries on local health outcomes

We further test whether the pandemic outbreak in neighboring countries can affect (or worsen) a country's own COVID-19 caseload. To investigate whether this may be the case, we examine empirically the effect of a country's "neighboring" COVID-19 cases on its own pandemic evolution. Namely, we create the following:

$$Neighbor\ Cases_{i,t} = \sum_{j=1}^{10} w_{i,j} * Cases_{j,t} \quad (6)$$

where $Neighbor\ Cases_{i,t}$ is a spillover term for COVID-19 cases in neighboring countries. $w_{i,j}$ are bilateral distance weights constructed between country *i* and country *j* based on the inverse of the distance between the ten closest foreign capital cities and country *i*'s own capital city, and where $\sum_{j=1}^{10} w_{i,j}$=1. $Cases_{j,t}$ refer to country *j*'s own COVID-19 infections as a share of population at time *t*. Then, the spillover term $Neighbor\ Cases_{j,t}$ captures COVID-19 cases in any given country's closest 10 foreign countries and capital cities. This term is introduced to equation (2) as following:

$$\Delta C_{i,t} = \mu_i + \gamma_t + \beta V_{i,t-l} + \gamma Neighbor\ Cases_{j,t-m} + \theta X_{i,t-l} + \varepsilon_{i,t} \quad (7)$$

All equations are estimated using OLS, with standard errors clustered at the country level.

IV. Determinants of vaccine rollouts

We begin by exploring the factors that determine the pace of vaccine rollout in a given country. We use cross-country data for this analysis, focusing on both supply and demand aspects which may affect the speed of vaccination and rollouts. From the supply side, notwithstanding the recent increase in production, the overall supply of vaccines has remained scarce. Hence, we focus on the timing and size of vaccine procurement (determined by the

procurement deals made by countries with producers in 2020 and 2021) as well as a dummy variable to capture whether the majority of vaccine is produced domestically or imported from abroad. We also look at various metrics that capture the health infrastructure of the country, which determines the country's ability to roll out vaccines quickly and efficiently. From the demand side, we look at factors such as how badly the country was affected by the pandemic—capturing the urgency on the part of both governments and the general public on getting vaccinated; and the attitude of the population towards getting vaccinated—which is likely to become increasingly important especially as a larger share of the population (the most willing) get vaccinated.

Figure 2 shows that there was considerable variation in the pace of vaccine procurement. In general, the US and the EU were faster in procuring vaccines, putting in orders even before the vaccines were approved and fully tested. This allowed them to capture the initial supply of vaccines as they became available at the end of 2020 and the early part of 2021. Lower income countries in general were not able to procure vaccines as quickly while others were more conservative with regards to early negotiations with potential (not approved) vaccine producers (Annex Figure A2). The latter was particularly true in countries that had the pandemic under control in the last quarter of 2020 (such as several Asian economies).

Table 1 reports results for univariate regressions of vaccine rollout on various factors (columns 1 through 5) as well as the multivariate regression as described in equation 1 in columns 6 and 7. Each factor has the expected sign and is statistically significant in the univariate regressions. Notably, the multivariate regressions based on the 4 factors are able to explain almost 60 percent of the observed cross-country variation in vaccination rollout.

Figure 3 summarizes the results from column 6 of Table 1, showing the impact of a one standard deviation change in different factors on vaccine rollout. From the supply side, it confirms that early procurement is significant in explaining the pace of subsequent vaccination rollout. A one standard deviation increase in procurement (confirmed orders plus potential deals) in January 2021 (corresponding to the difference between procurement for Israel which secured supply quickly, versus Germany where negotiations were more protracted) is associated with around a 4 percentage point higher vaccination rates at the end of June. Domestic production of vaccines is also associated with higher and faster vaccinations (see Table 1), probably reflecting the ability of producing countries to secure a larger share of vaccine and administer them faster (because of shorter delivery time).[17] In particular, we find that on average producers countries have vaccinate around 41 percent of their populations by June 20, 2021 relative to 20 percent for non-producers. Also of importance are countries' health infrastructure (Annex Figure A3, bottom right panel) resulting in a 6 percent increase in vaccinations for a one standard deviation increase in health infrastructure index constructed by the World Economic Forum—one standard deviation roughly corresponds to the gap between an average Asian country and an average country in Africa.

Turning to demand side factors, the largest impact on the pace of vaccinations comes from the severity of the pandemic in a given country during the first COVID-19 wave. There was wide variation in how badly countries were affected during the first wave, with countries in Europe and America affected more than countries in Asia (Annex Figure A3, top left panel), and

[17] Cross country analysis suggests that domestic production is significantly and positively associated with greater vaccine procurement. In addition, on average, procurement is higher for domestic producers relative to countries relying on the import of vaccines. Finally, controlling for the amount of vaccine, vaccine producer countries had higher rollouts.

this influenced how quickly countries vaccinated their population in the first half of 2021. On average, a one standard deviation increase in the number of confirmed COVID-19 cases per capita in 2020 is associated with a 10-percentage point increase in vaccinations till June 2021. The willingness of the population to accept the vaccine also varied (Annex Figure A3, top right panel) and was significant in explaining the difference in vaccination rollout—a one standard deviation change in vaccine acceptance (difference between Denmark, the country in our sample with the highest vaccine acceptance in January 2021, and Australia) resulting in a 2.3 percent increase in vaccinations. Similar results are obtained for other factors such as trust in government or political stability (Annex Figure A3, bottom right panel), which capture the attitude of the population towards authorities, and by extension, towards the vaccination campaigns (see Annex Table A2, column 6-7).

The results presented above are robust to alternate specifications. In particular, the results hold for alternate measures of procurement (for example, confirmed orders vs potential orders), procurement at different times (in October 2020, latest available data) and different data sources (Airfinity instead of Duke University)—see Annex Table A2, columns 1-5. Results also hold for alternative measures of health infrastructure, such as the Global Health Security Index or alternative measures such has doctors per capita or hospital beds per capita (Annex Table A2, columns 6-8). On the demand side, results are robust to alternate measures of COVID-19 impact—latest COVID-19 caseload (as of June 20, 2021), average number of daily confirmed cases in 2020, size of peak daily cases in 2020 and measures based on COVID-19 deaths as opposed to cases (Annex Table A2, columns 1-4). Finally, the dependent variable used for this analysis is the number of vaccinations per capita in June 2021. All the results are similar with

alternative measures, for example, the average number of daily vaccinations in 2021 (Annex Table A3, column 5).

V. Effects of vaccinations on health outcomes

A. Baseline

We start by examining the effect of increased vaccine coverage on new COVID-19 cases and deaths, the reproduction rate and COVID-19 related ICU hospitalizations using equation (2). Our results suggest that vaccinations have a large and statistically significant effect on confirmed COVID-19 cases. Under our baseline specification (Table 2, column 1), a 20 percentage points increase in the number of daily vaccinations per 100 population results in about a 0.02 decline in the daily COVID-19 cases per 100 population after 21 days, which is equivalent to around one standard deviation of daily COIVD-19 cases in our sample. This is both statistically and economically significant since we measure COVID-19 cases at the daily frequency, hence the measured decline in cases adds up over time. A similar result holds for the reproduction rate of the virus as well as COVID-19 related deaths and ICU hospitalizations as a share of population related to COVID-19.[18] ICU hospitalization rates also decline, indicating that fewer confirmed cases translate into serious illness as vaccination rates increase. The second dose of the vaccine further reduces the number of daily COVID-19 cases, but the impact is statistically significant only in the case of reproduction rate.

While our baseline specification measures the impact of vaccinations with a lag of 21 days, further exploration of the lag structure of the results suggests that the impact increases over

[18] The reproduction rate in the baseline estimated using 7 days of lag. This represents the average duration of illness during with the index patient infects others. We get similar results with 10, 14 and 21 days.

time, peaking at around 2-3 weeks after vaccination (Figure 4). This is in line with findings of the epidemiological literature, where the protection from vaccine builds up over time. The more immediate effect of vaccinations (statistically significant impact after 2-3 days) may be explained by behavioral factors—people that are waiting to get vaccinated were taking greater precautions before, practicing more social distancing, and reducing their mobility in anticipation of developing COVID-19 immunity soon (Engler et al., 2021). The results, consistent with Deb et al.(2020a), show that the stringency of containment measures also has a significant and negative impact on the spread of COVID-19, while higher mobility is associated with worse health outcomes.

The results are robust to different subsamples. Annex Table A4 summarizes the robustness results: (1) the results hold when the data is winsorized to ensure that the results are not driven by outliers; (2) our results also hold if we drop countries that started vaccinating late – started their vaccination campaigns after March 1—such as Colombia and Vietnam; (3) the results are also robust to dropping countries that started vaccinations very early such as the United States and Israel—already reached 5 percent of the population by February 1; (4) the results are not driven by a particular region as our results go through if we drop one region at a time from the analysis, though the impact of vaccination is not statistically significant if we drop European countries as the sample size shrinks significantly. Finally, the results are not driven by a particular country and all our results hold if we drop countries with high levels of vaccinations (such as the United States, the United Kingdom, or Israel).[19]

[19] Estimated coefficient when dropping one country at a time remains statistically significant and ranges from -0.00107 to -0.00071 (compared with the estimated coefficient of -0.000986 for the full sample). Results available upon request.

B. Role of containment measures, the severity of the outbreak, variants and type of vaccine

We extend our baseline specification to assess the role of factors such as the stringency of containment measures and the severity of the outbreak in shaping the impact of vaccines on health outcomes using equation (3-5).

Stringency of Containment Measures

Column 1-3 of Table 3 extends our baseline regression for COVID-19 cases by adding an interaction term between the share of population that has been vaccinated with one dose with the stringency of containment measures. The interaction terms are negative suggesting that an increase in vaccines reduces new COVID-19 cases more when they are complemented with more stringent containment measures. The results from the simple interaction are not statistically significant (column 1, equation 3) but the smooth transition (column 2, equation 4) and quartiles (column 3, equation 5) are significant, with the absolute value of the coefficient for the 3rd and 4th quartile being larger than the 2nd quartile. This suggests that the effect of containment measure in shaping the effectiveness of vaccines is not linear and it becomes significant at higher levels of containment. In particular, we find that at higher levels of stringency, the efficacy of vaccines in reducing cases is about 50 percent higher than at lower levels of stringency. This indicates complementarity between vaccines and containment measures, with the two policy tools reinforcing each other in containing outbreaks.

Severity of the Outbreak

The impact of vaccines on COVID cases is also likely to depend on the stage of the outbreak. If a country is in the middle of a significant outbreak, an increase in vaccine rollout is likely to lead to a bigger decline in new cases. To test this hypothesis, column 4-6 of Table 3

adds an interaction term between the share of population that has been vaccinated with one dose with the number of new cases (smoothed by a moving average over seven days) in the country. Column 4 uses simple interaction, column 5 smooth transition and in column 6 the number of new cases is categorized into quartiles. The interaction terms are negative and significant (the absolute value of the coefficient increasing for each higher quartile) once again indicating that an increase in vaccines reduce new cases by more when initial cases were high to begin with.[20] Given the larger health gains in countries with severe outbreaks, and conversely the diminishing returns to vaccine rollout in countries with limited COVID cases, this highlights the scope for countries to share their vaccine supply with other countries once they reach high level of vaccination.[21]

Variants and type of vaccine

The spread of new variants of COVID-19, in particular the Delta variant that has spread rapidly in since Spring 2021, have raised concerns that existing vaccines may not be as effective against new variants. While data is still emerging, we find early evidence consistent with epidemiological studies that suggests that a larger share of the Delta variant makes vaccines less effective. Table 4 presents our regressions results where we interact vaccine first dose with the share of Delta variant in the total number of samples sequenced. Column 1 allows for the simple

[20] The results reported in columns 1 and 2 of Table 3 are of course related, in the sense that higher stringency in containment measures may be a response to higher COVID-19 cases. If we include the interaction terms of the quartiles for stringency as well as new cases together in the same regression, the coefficient signs remain the same though the stringency interactions become insignificant, indicating that the severity of the outbreak may be the more important factor determining the effect of the vaccine rollout.

[21] We also explored whether vaccination rates impact health outcomes non-linearly by including square and cubic terms of the vaccination to population ratio in the baseline regression. These higher order terms were insignificant, potentially reflecting the fact that not enough countries have reached high enough vaccination rates to approach herd immunity, in part because the new, more transmissible, variants of the virus may have raised herd immunity thresholds.

interaction between share of population vaccinated with the first dose with the share of Delta variant detected (equation 3). The interaction term is positive and significant, indicating that a higher share of Delta decreases the impact of vaccines on COVID-19 cases. Column 2 uses a smooth transition function (equation 4) and shows that while vaccines remain effective in both cases (low and high share of Delta variant), the effectiveness is reduced by half when the Delta variant is dominant. The results for different quartiles of the share of Delta variant (equation 5) are not statistically significant (column 3) but point in the same direction and are likely to improve as more data becomes available allowing us to estimate the effects more precisely. We get similar results when using the vaccine second dose.

A related question is about to the efficacy of different vaccines. While the medical-scientific literature is best placed to answer this question, tentative results based on the share of mRNA vaccines relative to non-mRNA vaccine presented in Table 5 suggests that mRNA vaccines may be more effective. Although consistent with recent epidemiological studies (see Olliaro et al., 2021), this result needs to be interpreted with caution given data limitations—our data on mRNA vaccines is static and captures a snapshot on June 20, 2021 which may not capture the timing of when the different vaccines became available; and the majority of early vaccine adopters (advanced countries in North America and Europe) used mRNA vaccines and this may bias the results against finding an effect for non-mRNA vaccines.[22]

[22] To account for the latter, we controlled for the share of vaccination (both linear and non-linear) and the results remain robust, albeit weaker. We also control for early adopters and the results continue to hold.

C. Evidence of pandemic spillovers from neighboring countries

The analysis has thus far provided evidence on the importance of vaccines in controlling the COVID-19 pandemic, lowering infections and fatalities, and reducing the reproduction rate. However, while it may be that a country quickly and efficiently vaccinates its population while putting in place stringent containment measures, there may be countering effects which are not related to a country's own policies, but that nonetheless may diminish the progress that a country makes in controlling its local outbreak. Indeed, progress in vaccinations may be hampered by "spillovers" of COVID-19 cases from other countries, namely those which are closer in proximity, share borders, or neighbor each other. This in turn can lengthen the duration of the pandemic and worsen its health outcomes. To investigate whether this may be the case, we use equations (6) and (7) to empirically assess the effect of a country's neighboring COVID-19 cases on its own pandemic evolution.

The results, reported in Table 6, provide evidence that pandemics in a country's neighbors can derail efforts to reduce COVID-19 infections domestically. Namely, the results show that a one percentage point increase in the neighboring COVID-19 caseload as a share of the population is likely to "spillover" to close-by countries, where domestic COVID-19 infections as a share of the population will increase by 0.5 percentage point after 7 days. This effect is persistent across our analysis' time horizon and at different lags, (Figure 5), though it diminishes in magnitude over time. For additional robustness, we also create spillover terms using alternative sets of weights. In particular, we first broaden our specification to create bilateral distance weights to all capital cities worldwide, so that we capture a country's linkages

with all other countries[23]. Second, we also create bilateral trade weights based on a country *i*'s imports and exports exposure to country *j* to factor in economic relationship in addition to proximity. The results, reported in Annex Table A2, are robust to these alternative specifications, and show a higher magnitude of spillovers from a neighboring country's COVID-19 caseload.

Large negative health spillovers from neighboring countries, in conjunction with the result from the previous sub-section that vaccines provide larger health gains in countries with severe outbreaks, thus provide a compelling rationale for vaccine sharing (especially with countries facing high COVID cases). Vaccinating early and broadly, not only a country's own population but also all other countries' populations, can then limit COVID-19 spillovers into an own nation and bring a swifter end to the pandemic abroad. These results are consistent with Agarwal and Gopinath (2021) who stress the importance of vaccinating a large share of the global population as quickly as possible, noting that "the pandemic is not over anywhere unless it is over everywhere."

The results are not driven by reverse causality. We employ an Instrumental Variable (IV) approach to address endogeneity which may arise from uncontrolled factors which affect domestic and neighboring cases. For this purpose, we consider the share of the population which has been vaccinated in the 10 closest neighboring countries, based on distance between capital cities as an instrument. The basic identifying assumption is that vaccination levels in foreign countries are strongly correlated with new COVID-19 in the corresponding foreign country, but not be correlated with daily shocks affecting domestic COVID-19 cases or the evolution of the

[23] Given that bilateral distance weights are created using the inverse of the distance between two cities, the closer the city, the higher its weight.

pandemic locally, after accounting for local vaccination. In particular, our IV strategy reads as follows:

$$\Delta C_{i,t} = \mu_{i,t} + \beta V_{i,t} + \gamma \widehat{Neighbor\ Cases}_{J,t-7} + \ \theta X_{i,t-l} + \ \varepsilon_{i,t} \qquad (6)$$

with

$$\widehat{Neighbor\ Cases}_{J,t-7} = \ \alpha + \ \mu_{j,t} + \beta Neighbor\ Vaccines_{j,t-28} + \ \theta X_{j,t-l} + \ \varepsilon_{j,t} \qquad (7)$$

where $Neighbor\ Vaccines_{j,t-28}$ denotes the share of population vaccinated in neighboring countries 28 days before—the 21 day gap is thus kept consistent with our baseline results given that neighbor cases are lagged 7 days, so that the peak impact of vaccinations materializes after 21 days. The first stage estimates of the results suggest that the instrument is statistically significant: The Kleibergen-Paap rk Wald F statistic, equivalent to the F-effective statistic for non-homoscedastic error in case of one endogenous variable and one instrument (Andrews et al., 2019)— is 45 (column 3) and 11.75 (column 4) respectively, in the first case well above the associated Stock-Yogo critical values for non-spheric disturbances. The IV results are reported in Table 4 columns (3) and (4), and are consistent with the baseline OLS results shown in columns (1) and (2). The results also indicate that neighboring COVID-19 cases can significantly lead to an increase in the number of domestic COVID-19 cases 7 days later, though the magnitude of the IV coefficient is slightly larger than that of the OLS estimates.[24]

[24] Domestic vaccinations are statistically insignificant in the IV regressions because of their high correlation with vaccinations abroad.

VI. Conclusion

This paper provides an empirical assessment of the determinants of vaccine rollouts in a cross-country setting, as well as the impact of COVID-19 vaccinations on health outcomes. We use a novel daily database on vaccine rollouts, new COVID-19 cases and deaths, the COVID-19 reproduction rate, COVID-19 ICU admissions, as well as data on non-pharmaceutical interventions and mobility. The daily database is combined with data on vaccine procurements, production, vaccine acceptance and health infrastructure. To the best of our knowledge, this is the first attempt to empirically assess the effects of COVID-19 vaccines at such a large scale (with a country sample of 126 countries), while also examining the role of country-specific conditions, and the impact of the pandemic in neighboring countries.

The results on the determinants of vaccine rollout suggest that from the supply side, early procurement, domestic production of vaccines, and countries' health infrastructure are important factors in determining the speed of rollout in a given country. Meanwhile, looking at demand side factors, the largest impact on the pace of vaccinations comes from the severity of the pandemic in a given country during the first COVID-19 wave, while the willingness of the population to accept the vaccine also contributes to a more rapid pace of vaccination in a country.

Turning to the effects of COVID-19 vaccines on health outcomes, we find that vaccinations have a large and statistically significant effect on new COVID-19 cases, deaths, and ICU admissions as a share of population, and the reproduction rate of the virus. Vaccinations also reduces the number of ICU patients per infected person, thereby enhancing the health system's resilience to cope with the spread of the virus and potentially reducing the need for very strict and broad-based containment measures. Meanwhile, the second dose of the vaccine, further

reduces the number of daily COVID-19 cases, but the impact is statistically significant only in the case of the reproduction rate. These results are robust to alternative specifications and samples.

In addition, we find that the effect of COVID-19 vaccines varies depending on country-specific conditions, such as the level of stringency measures imposed in a country during the vaccine rollout, as well as the severity of the pandemic outbreak in a country. Specifically, the results provide evidence that COVID-19 vaccines are more effective in reducing new COVID-19 infections when complimented with stringent containment measures. Similarly, we find that the impact of vaccines on COVID cases varies depending on the stage of the outbreak, with an increase in vaccine rollouts being more likely to lead to a bigger decline in new cases if a country is in the middle of a significant outbreak. This suggests that vaccines should be channeled where possible, to countries facing more acute outbreaks. Finally, while the data is still emerging, we find early evidence consistent with epidemiological studies that suggests that the presence of more infectious variations of COVID-19, such as the Delta variant, makes vaccines less effective, while vaccinations using mRNA vaccines have a greater marginal impact relative to their non-mRNA counterparts.

The results also provide evidence on the importance of controlling the pandemic not only locally, but also globally (see Agarwal and Gopinath, 2021). We find that spillovers from COVID-19 cases in neighboring countries are significant and lead to an increase in an own country's caseload, therefore hampering efforts in taming its own local outbreak despite vaccinations and containment measures. In conjunction with the result that vaccines provide larger health gains in countries with severe outbreaks (or conversely there are diminishing returns to vaccine rollout in countries with limited COVID cases), this highlights the potential

gains from vaccine sharing. Vaccinating early and broadly not only a country's own population, but also all other countries' populations, especially those with large outbreaks, can thus limit COVID-19 spillovers into an own nation, minimize the loss of lives, and bring a swifter end to the pandemic abroad.[25]

The findings in this paper, combined with results from Deb et al. (2021c) on the beneficial effects of vaccines on economic outcomes, highlight the importance of vaccines to address the crisis instigated by the COVID-19 pandemic (see also IMF, 2021). In addition to the direct health and economic benefits of vaccines, this paper finds evidence for the role of containment measures in complementing COVID-19 vaccines, and the importance of vaccine-sharing to limit pandemic spillovers. By providing quantitative empirical estimates on the determinants of vaccine rollouts and the effects of COVID-19 vaccines, our paper can help policymakers make informed decisions about local and global distributions of vaccines, as well as related policy tools, such as containment measures.

[25] As the number of countries with high vaccination rates remain limited at the time of writing, the paper was not able to explore the potential non-linear effects of vaccines on health outcomes. Similarly, an exploration of whether health outcomes are worse in countries with higher levels of vaccine hesitancy require more countries to reach levels of vaccination where hesitancy becomes a binding factor in vaccine rollouts. Exploring such effects could be an interesting avenue for future research. If returns to vaccine were to diminish after a certain point, then this would add another rationale for sharing vaccine doses more equitably across countries.

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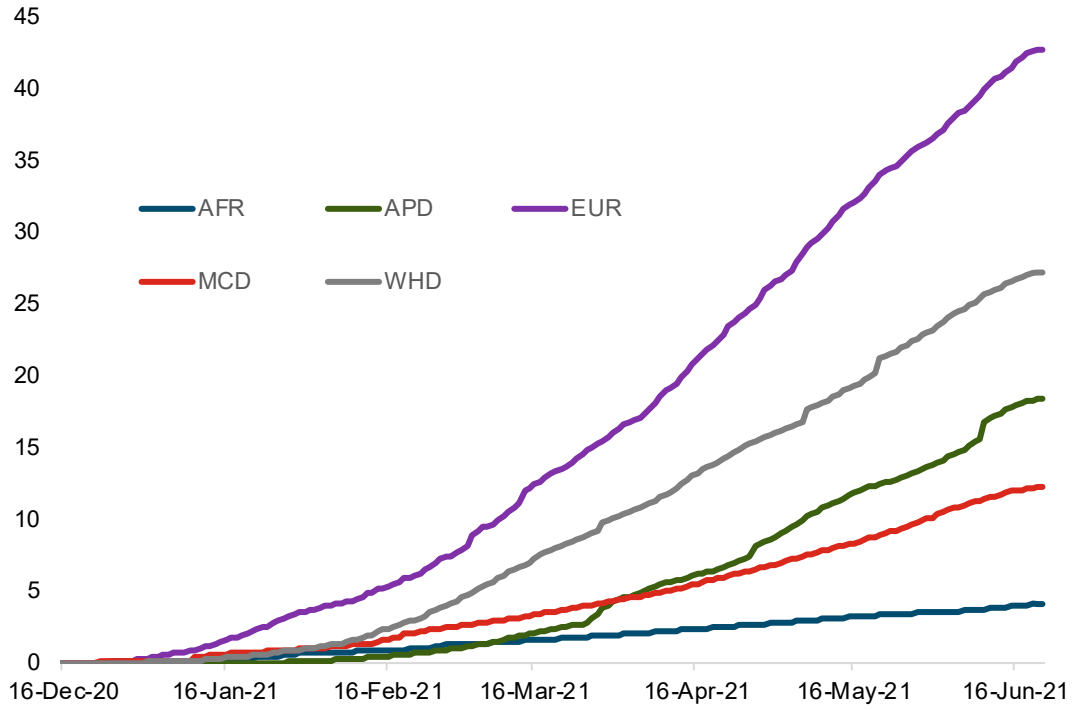
Figures

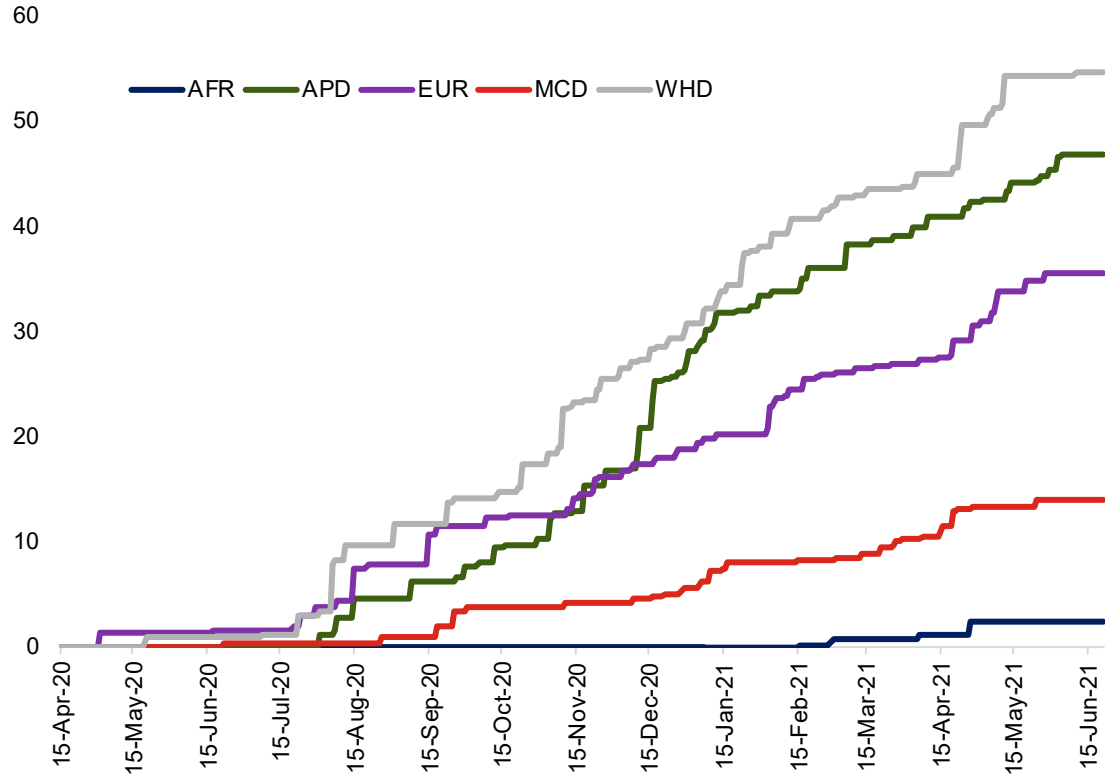
Figure 1. Vaccinations across regions (simple average, per 100 population)



Source: Our World in Data.

Note: AFR: Sub-Saharan Africa; APD: Asia Pacific Department; EUR: European Department; MCD: Middle East and Central Asia Department; WHD: Western Hemisphere Department.

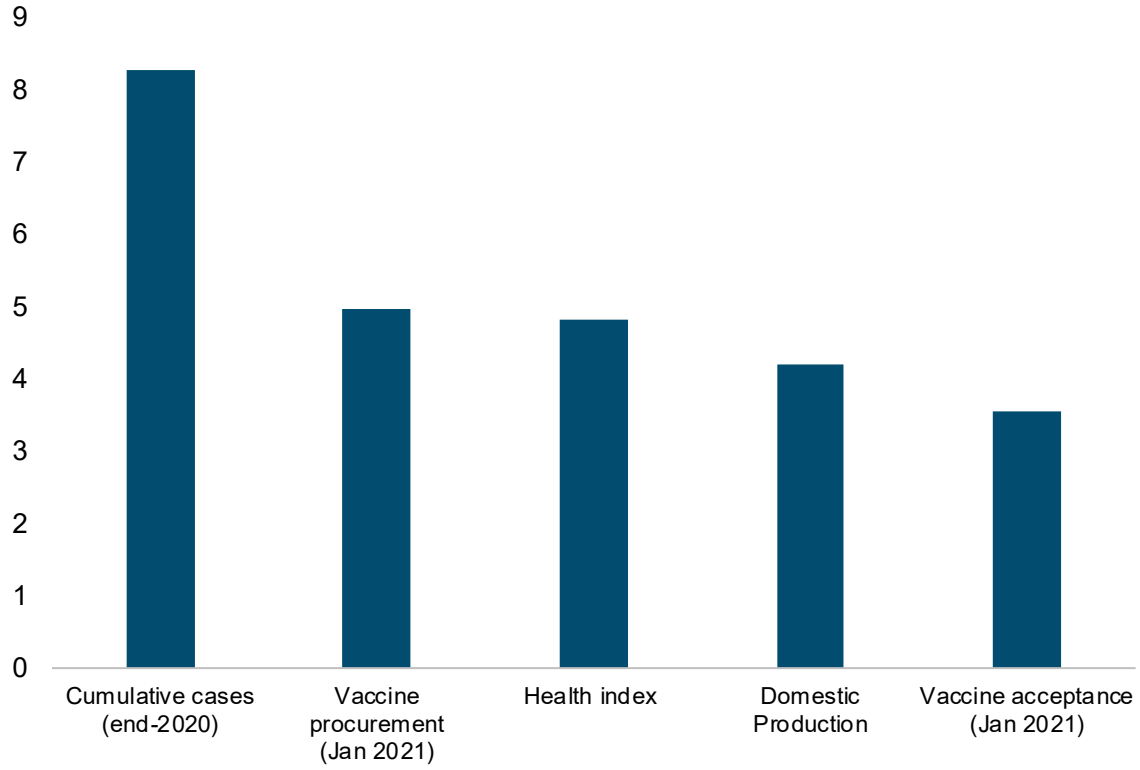
Figure 2. Vaccine procurements per region (orders including potential orders, per 100 population)



Note: The chart includes confirmed vaccine orders, potential procurement deals and donations.

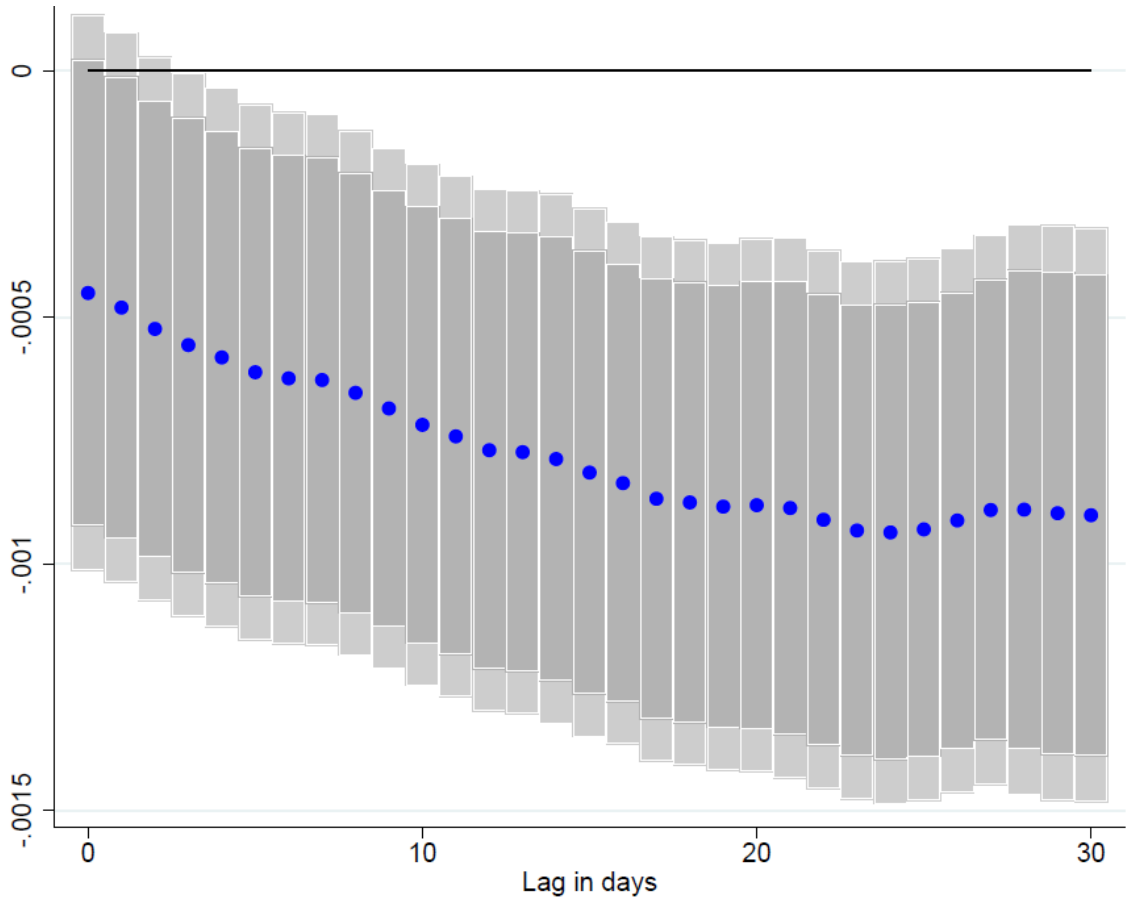
Source: Duke University Heath Innovation Center and IMF Staff calculations.

Figure 3. Factors affecting vaccine rollouts (vaccinations per 100 population, impact of 1 standard deviation change in factor)



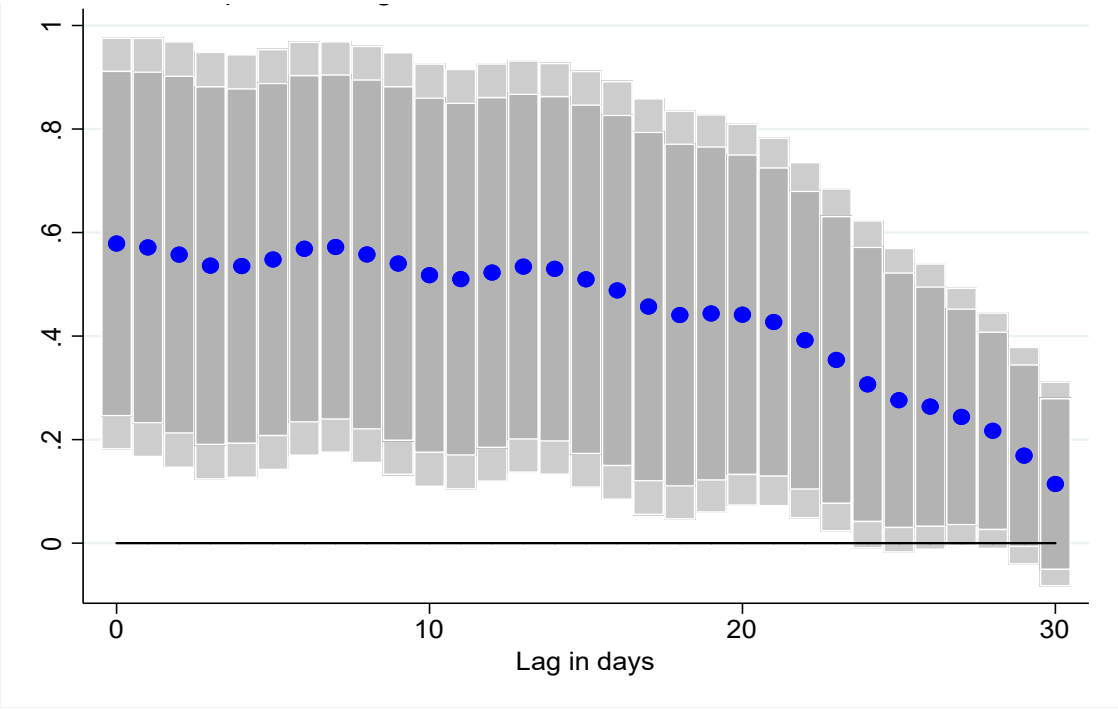
Note: The figure reports the impact of one standard deviation change in different factors on the share of population that is vaccinated with at least one dose based on estimates using equation (1).

Figure 4. Effect of vaccinations on new COVID-19 cases, at different lags.



Note: Coefficient β is reported for each lag ℓ (1-30), and based on $\Delta C_{i,t} = \alpha + \mu_i + \gamma_t + \beta V_{i,t-l} + \theta X_{i,t-l} + \varepsilon_{i,t}$ for a sample of 126 countries using daily data from December 20, 2020–June 16, 2021. where $C_{i,t}$ denotes: the number of cumulative COVID-19 cases. $V_{i,t-l}$ denotes the share of the individuals in the population which have received at least one vaccine shot. μ_i and γ_t are country and time fixed effects. X is a vector of control variables which includes the lagged level of cumulative cases, the stringency of containment measures index, and mobility indices. ℓ denotes the lags in the response of new COVID-19 cases. Lightly shaded bars denote 90 percent confidence bands, and dark-shared bars denote 95 percent confidence bands.

Figure 5. Effect of neighboring new COVID-19 cases on domestic COVID-19 cases at different lags



Note: Coefficient γ is reported for each lag ℓ (1-30), and based on $\Delta C_{i,t} = \alpha + \mu_i + \gamma_t + \beta V_{i,t-l} + \gamma Neighbor\ Cases_{i,t} + \theta X_{i,t-l} + \varepsilon_{i,t}$ for a sample of 123 countries using daily data from December 20, 2020–June 16, 2021. where $C_{i,t}$ denotes: the number of cumulative COVID-19 cases. $Neighbor\ Cases_{i,t}$ is a spillover term for COVID-19 cases in neighboring countries. $V_{i,t-l}$ denotes the share of the individuals in the population which have received at least one vaccine shot. μ_i and γ_t are country and time fixed effects. X is a vector of control variables which includes the lagged level of cumulative cases, the stringency of containment measures index, and mobility indices. ℓ denotes the lags in the response of new COVID-19 cases. Lightly shaded bars denote 90 percent confidence bands, and dark-shared bars denote 95 percent confidence bands.

Tables

Table 1. Cross sectional regression of vaccine rollout

VARIABLES	(1) Total	(2) Total	(3) Total	(4) Total	(5) Total	(6) Total	(7) Total	(8) Total
Potential procurement (Jan 2021)	0.0690***					0.0480***		0.0534***
	(0.0159)					(0.0151)		(0.0161)
Domestic Production		20.61***					7.435*	8.897**
		(3.075)					(3.770)	(3.702)
Cumulative cases (end-2020)			5.717***			5.401***	4.293***	4.617***
			(0.807)			(0.977)	(1.047)	(1.081)
Health index (WEF)				14.07***		8.760***	9.535***	7.360***
				(1.433)		(2.347)	(2.378)	(2.164)
Vaccine acceptance (Jan 2021)					52.45***	29.80***	31.98***	25.99**
					(11.86)	(11.19)	(10.88)	(10.74)
Constant	22.55***	20.23***	14.15***	-62.97***	-11.35	-64.32***	-68.67***	-54.17***
	(1.703)	(1.795)	(1.777)	(8.453)	(8.003)	(14.29)	(13.92)	(13.05)
Observations	202	202	196	133	95	85	85	85
R-squared	0.042	0.122	0.251	0.355	0.135	0.570	0.549	0.602

Note: Table reports results for equation (1). The dependent variable is the share of population that is vaccinated with at least one dose. Robust standard errors. ***, **, and * represent statistical significant at 1, 5 and 10 percent respectively

Table 2. Baseline results on the impact of vaccination on health outcomes

	(1) Cases/Pop	(2) Cases/Pop	(3) R-value	(4) R-value	(5) Deaths/Pop	(6) Deaths/Pop	(7) ICU/Pop	(8) ICU/Pop	(9) ICU/Cases
First vaccine dose/population	-0.000986***	-0.000898***	-0.013707***	-0.010507***	-0.000008*	-0.000009*	-0.000127***	-0.000122**	-0.007801***
	(0.000)	(0.000)	(0.004)	(0.004)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)
Second vaccine dose/population		-0.000222		-0.007932**		0.000003		-0.000015	
		(0.000)		(0.004)		(0.000)		(0.000)	
Containment measures	-0.009603	-0.010365	-0.505722***	-0.543493***	-0.000214*	-0.000208*	0.001605	0.001454	
	(0.008)	(0.008)	(0.165)	(0.164)	(0.000)	(0.000)	(0.002)	(0.002)	
Mobility	0.000100**	0.000103***	0.002664**	0.002756**	0.000002**	0.000002**	0.000020	0.000020	
	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	
Lagged cases/pop	0.001610	0.001816					0.002710***	0.002742***	
	(0.003)	(0.003)					(0.001)	(0.001)	
Lagged reproduction rate			-1.059113***	-1.057343***					
			(0.018)	(0.018)					
Lagged deaths/pop					0.003925	0.003964			
					(0.004)	(0.004)			
Lagged ICU/Cases									0.000475
									(0.008)
Constant	-1.973306	-1.318626	49.398938**	67.91842***	0.002448	0.002879	-0.058064	-0.045988	-4.735857
	(1.544)	(1.768)	(23.416)	(22.226)	(0.014)	(0.014)	(0.211)	(0.233)	(4.652)
Observations	13,542	13,455	13,468	13,385	11,122	11,096	3,258	3,257	3100
R-squared	0.624	0.625	0.537	0.535	0.720	0.720	0.834	0.834	0.633
Lags 1st dose/2nd dose	21	21/7	21	21/7	42	42/28	21	21/7	21
Health policy controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of countries	126	126	125	125	123	123	22	22	23

Note: Table reports results for equation (2). The dependent variable is new COVID-19 cases, reproduction rate, COVID-19 deaths, and ICU admissions due to COVID-19 as a share of population. The regressions control for stringency of containment measures, other non-pharmaceutical interventions and health policy controls, mobility, lagged cases, deaths or reproduction rate, country specific time trends, as well as country and time fixed effects. First vaccine and control variables are lagged by 42 days for deaths (columns 5 and 6) and 21 days for all other columns. Standard errors are clustered at the country level. ***, **, and * represent statistical significant at 1, 5 and 10 percent respectively.

Table 3. Role of stringency measures and pandemic severity on vaccination outcomes

	(1) Cases	(2) Cases	(3) Cases	(4) Cases	(5) Cases	(6) Cases
Vaccine first dose	-0.000216		-0.000623*	-0.000443**		-0.000024
	(0.001)		(0.000)	(0.000)		(0.000)
Interaction with Containment Measures						
Containment measures * Vaccine first dose	-0.000982					
	(0.001)					
Low containment measures * Vaccine first dose		0.000053				
		(0.000)				
High containment measures * Vaccine first dose		-0.001504***				
		(0.000)				
2nd Quartile of containment measures * Vaccine first dose			-0.000292*			
			(0.000)			
3rd Quartile of containment measures * Vaccine first dose			-0.000350**			
			(0.000)			
4th Quartile of containment measures * Vaccine first dose			-0.000354*			
			(0.000)			
Interaction with New Cases						
New cases * Vaccine first dose				-0.012338**		
				(0.005)		
Low new cases * Vaccine first dose					-0.000892***	
					(0.000)	
High new cases * Vaccine first dose					-0.000885**	
					(0.000)	
2nd Quartile of new cases * Vaccine first dose						-0.000271**
						(0.000)
3rd Quartile of new cases * Vaccine first dose						-0.000586***
						(0.000)
4th Quartile of new cases * Vaccine first dose						-0.000801***
						(0.000)
Observations	13,455	13,455	13,455	13,455	13,455	13,455
R-squared	0.625	0.627	0.628	0.637	0.624	0.637
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
No. of countries	126	126	126	126	126	126
P-value F-test		0.00574			0.987	

Note: The dependent variable is new COVID-19 cases as a share of population. The percent of population that has received 1 vaccine dose is interacted with the stringency of containment measures (columns 1-3) and the level of new cases (moving average over 7 days, columns 4-6). Column 1 and 4 allows for the simple interaction (equation 3). Column 2 and 5 uses a smooth transition function (equation 4), while column 3 and 6 categorizes the interaction variables into 4 quartiles (equation 5). The vaccine variable as well as the interaction terms are lagged 21 days. All regressions control for stringency of containment measures and other non-pharmaceutical interventions (21 lags), the percent of population that has received two doses (7 lags), mobility (21 lags), country specific time trends, as well as country and time fixed effects. Standard errors are clustered at the country level. *** p<0.01, ** p<0.05, * p<0.1

Table 4. Role of variants on vaccination outcomes

VARIABLES	(1) Cases Simple interaction	(2) Cases Smooth transition	(3) Cases Quartiles
Vaccine first dose per capita	-0.000790***		-0.000936***
	(0.000)		(0.000)
Interaction with Delta variant			
Delta share * Vaccine first dose	0.000707***		
	(0.000)		
Low share of Delta * Vaccine first dose		-0.001331***	
		(0.000)	
High share of Delta * Vaccine first dose		-0.000584*	
		(0.000)	
2nd quartile of Delta * Vaccine first dose			-0.000044
			(0.000)
3rd quartile of Delta * Vaccine first dose			0.000126
			(0.000)
4th quartile of Delta * Vaccine first dose			0.000333
			(0.000)
Observations	8,485	8,485	8,485
R-squared	0.591	0.588	0.590
Health policy controls	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
No. of countries	75	75	75

Note: The dependent variable is new COVID-19 cases as a share of population. The percent of population that has received 1 vaccine dose is interacted with the share of Delta variant in the total number of samples sequenced. Column 1 allows for the simple interaction (equation 3) between share of population vaccinated with the first dose with the share of Delta variant detected. Column 2 uses a smooth transition function (equation 4), while column 3 categorizes the share of Delta variant into 4 quartiles (equation 5). The vaccine variable is lagged 21 days. All regressions control for stringency of containment measures and other non-pharmaceutical interventions (21 lags), mobility (21 lags), country specific time trends, as well as country and time fixed effects. Standard errors are clustered at the country level. *** p<0.01, ** p<0.05, * p<0.1

Table 5. Role of type of vaccine on vaccination outcomes

VARIABLES	(1) Cases Dummy interaction	(2) Cases Simple interaction	(3) Cases Smooth transition	(4) Cases Quartiles
Vaccine first dose per capita	-0.000404	-0.000320		0.000129
	(0.000)	(0.000)		(0.000)
Interaction with share of mRNA vaccine				
mRNA share * Vaccine first dose	-0.000745*			
	(0.000)			
mRNA share * Vaccine first dose		-0.000942*		
		(0.000)		
Low share of mRNA * Vaccine first dose			0.000415	
			(0.000)	
High share of mRNA * Vaccine first dose			-0.001431***	
			(0.000)	
3rd quartile of mRNA * Vaccine first dose				-0.000588
				(0.001)
4th quartile of mRNA * Vaccine first dose				-0.001310**
				(0.001)
Observations	13,542	13,239	13,239	13,239
R-squared	0.625	0.625	0.625	0.625
Health policy controls	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
No. of countries	126	122	122	122

Note: The dependent variable is new COVID-19 cases as a share of population. The percent of population that has received 1 vaccine dose is interacted with the share of mRNA vaccines to total vaccines as of June 20, 2021. Column 1 uses a dummy variable (equation 3), which takes the value 1 if the share of mRNA vaccines is greater than 50 percent, 0 otherwise. Column 2 allows for the simple interaction (equation 3) between share of population vaccinated with the first dose with the share of mRNA vaccines. Column 3 uses a smooth transition function (equation 4) while column 4 categorizes the share of mRNA vaccines into quartiles (equation 5). Given the uneven distribution, only the 3rd and 4th quartile are included, with all countries that do not use mRNA vaccines comprising of the residual omitted group. The vaccine variable is lagged 21 days. All regressions control for stringency of containment measures and other non-pharmaceutical interventions (21 lags), mobility (21 lags), country specific time trends, as well as country and time fixed effects. Standard errors are clustered at the country level. *** p<0.01, ** p<0.05, * p<0.1

Table 6. Effect of neighboring new COVID-19 cases on domestic new COVID-19 cases

	OLS	OLS	IV	IV
	(1)	(2)	(3)	(4)
	New COVID-19 Cases	New COVID-19 Cases	New COVID-19 Cases	New COVID-19 Cases
Vaccinated persons, 1 dose	-0.000973***	-0.000866***	-0.000325	-0.000183
	(0.000)	(0.000)	(0.000)	(0.000)
Vaccinated persons, 2 doses		-0.000285		-0.000199
		(0.000)		(0.000)
Neighbor cases (7 days lag)	0.566195***	0.572086***	0.638675*	0.680740**
	(0.204)	(0.203)	(0.364)	(0.325)
Containment measures index (lag)	-0.010388	-0.011402	-0.001193	-0.001202
	(0.008)	(0.008)	(0.002)	(0.003)
COVID-19 cases (lag)	-0.000113	0.000155	0.000579	-0.000085
	(0.003)	(0.003)	(0.006)	(0.005)
Mobility (lag)	0.000098***	0.000103***	0.000018	0.000022
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	13,241	13,154	13,241	13,154
R-squared	0.639	0.640	0.136	0.138
Health Policy Controls	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Kleibergen-Paap rk Wald F statistic			45.025	11.175
No. of countries	123	123	123	123
Vaccination 1 Lags	21 days	21 days	21 days	21 days
Vaccination 2 Lags	7 days	7 days	7 days	7 days

Note: Table reports results for equation (7). The dependent variable is new COVID-19 cases. A spillover term "Neighbor cases" (lag 7 days) is introduced to the equation to capture the effects of neighboring COVID-19 new cases on a country's own caseload using bilateral distance weights (equation 6). The regressions control for stringency of containment measures, other non-pharmaceutical interventions and health policy controls (21 lags), lags of mobility (21 lags), lagged new cases, country-specific time-trends, as well as country and time fixed-effects. Standard errors are clustered at the country level. ***, **, and * represent statistical significant at 1, 5 and 10 percent respectively.

Annex Table A.1: Summary Statistics

Panel A: Summary Statistics for Time-Varying data

	Obs.	Mean	Std. Dev.	Min	Max	Source	Starting Date	No. of countries
New COVID-19 Cases per 10000 population	71,896	1.01	2.34	0.00	182.94	JHU	22-Jan-20	210
New COVID-19 Deaths per 10000 population	46,569	0.03	0.06	0.00	2.67	JHU	22-Jan-20	200
Vaccinations per 100 population (1st dose)	23,257	13.26	17.73	0.00	116.15	OWID	16-Dec-20	202
Vaccinations per 100 population (2nd dose)	15,257	9.59	14.27	0.00	114.86	OWID	27-Dec-20	180
ICU Admissions per 10000	9,680	0.27	0.27	0.00	1.93	OWID	28-Jan-20	23
Procurement per 100 (confirmed)	22,367	42.93	73.09	0.04	520.10	Duke	1-May-20	101
Procurement per 100 (potential)	22,689	55.53	101.88	0.04	824.70	Duke	1-May-20	102
Stringency	90,576	0.56	0.23	0.03	1.00	OxCGRT	20-Jan-20	184
Retail Mobility	63,740	-21.66	25.07	-100.00	181.00	Google	15-Feb-20	135
Vaccine Acceptance	12,972	0.71	0.14	0.20	0.97	UMD	21-Dec-20	100

Panel B: Summary Statistics for Cross-Sectional data

	Obs.	Mean	Std. Dev.	Min	Max	Source	Date
Health Index	137	6.15	0.93	2.67	6.98	WEF	2019
Global Health Security Index	191	40.58	14.41	16.20	83.50	GHS	2019
Beds per 1000 people	204	3.06	2.42	0.10	13.80	World Bank	Latest reported
Physicians per 1000 People	237	1.80	1.60	0.01	8.42	World Bank	Latest reported

Annex Table A2. Robustness Checks - Rollout

	(1) Confirmed Procurement - Jan 2021	(2) Confirmed Procurement - Oct 2020	(3) Potential Procurement - Oct 2020	(4) Confirmed Procurement - latest	(5) Procurement - Airfinity	(6) GHS Health	(7) Doctors	(8) Hospital Beds
Procurement (Jan 2021)	0.0669***							
	(0.0207)							
Cumulative cases (end-2020)	5.502***	5.173***	5.154***	5.242***	5.782***	5.639***	3.771***	6.425***
	(0.978)	(0.941)	(0.937)	(0.990)	(1.436)	(1.016)	(1.097)	(0.985)
Health index (WEF)	8.327***	9.547***	9.715***	9.201***	9.880***			
	(2.318)	(2.334)	(2.340)	(2.428)	(3.226)			
Vaccine acceptance (Jan 2021)	30.80***	30.11***	29.91***	30.58***	3.269	16.20	41.54***	42.54***
	(10.93)	(11.21)	(11.23)	(11.26)	(14.10)	(10.76)	(9.758)	(12.05)
Procurement (Oct 2020)		0.0802***						
		(0.0271)						
Potential procurement (Oct 2020)			0.0570***					
			(0.0167)					
Potential procurement (latest)				0.0300**				
				(0.0128)				
Procurement (Airfinity)					0.0298***			
					(0.0108)			
Potential procurement (Jan 2021)						0.0392**	0.0480***	0.0619***
						(0.0165)	(0.0164)	(0.0133)
Health index (GHS)						0.489***		
						(0.148)		
Doctors per capita							6.567***	
							(1.268)	
Hospital beds per capita								1.125*
								(0.580)
Constant	-62.74***	-68.05***	-68.86***	-67.23***	-57.21***	-23.13***	-28.38***	-23.63***
	(14.16)	(14.00)	(13.98)	(14.44)	(20.36)	(6.292)	(6.443)	(8.139)
Observations	85	85	85	85	54	92	91	90
R-squared	0.577	0.558	0.560	0.557	0.494	0.601	0.684	0.554

Note: Table reports results for equation (1). The dependent variable is the share of population that is vaccinated with at least one dose. Robust standard errors. ***, **, and * represent statistical significant at 1, 5 and 10 percent respectively.

Annex Table A3. Robustness Checks - Rollout

	(1) Latest caseload	(2) Average cases in 2020	(3) Peak cases in 2020	(4) Deaths in 2020	(5) Daily vaccinations	(6) Trust in Government	(7) Political Stability
Potential procurement (Jan 2021)	0.0497***	0.0387**	0.0480***	0.0337*	3.587**	0.0312*	0.0356**
	(0.0141)	(0.0169)	(0.0151)	(0.0199)	(1.468)	(0.0172)	(0.0177)
Cumulative cases (latest)	2.917***						
	(0.459)						
Health index (WEF)	7.660***	10.97***	8.760***	13.98***	931.1***	8.612***	6.274***
	(2.153)	(2.506)	(2.347)	(3.099)	(249.0)	(1.489)	(1.197)
Vaccine acceptance (Jan 2021)	30.10***	26.07**	29.80***	27.03**	2,152**		
	(11.14)	(10.63)	(11.19)	(12.96)	(914.7)		
Average cases (2020)		18.54***					
		(4.270)					
Peak cases (2020)			5.401***				
			(0.977)				
Cumulative deaths (end-2020)				64.31			
				(54.74)			
Cumulative cases (end-2020)					438.5***	3.361***	2.941***
					(102.2)	(0.907)	(0.936)
Trust in Government (WEF)						3.792***	
						(1.126)	
Political Stability (World Bank)							8.914***
							(1.815)
Constant	-59.38***	-73.49***	-64.32***	-86.96***	-6,035***	-48.75***	-21.25***
	(14.00)	(15.27)	(14.29)	(18.13)	(1,365)	(7.669)	(6.464)
Observations	85	85	85	85	86	133	133
R-squared	0.607	0.549	0.570	0.408	0.448	0.479	0.540

Note: Table reports results for equation (1). The dependent variable is the share of population that is vaccinated with at least one dose, except for column (5) where it is the average number of daily vaccinations since the start of the vaccination campaign in the country. Robust standard errors. ***, **, and * represent statistical significant at 1, 5 and 10 percent respectively.

Annex Table A4. Robustness Checks – Impact of Vaccines on Health Outcomes

	(1) 1% winsorized	(2) drop late: start after March 1	(3) drop early: 5% before Feb 1	(4) without APD	(5) without EUR	(6) without MCD	(7) without WHD	(8) without AFR
Vaccine 1st dose per capita	-0.000910***	-0.001011***	-0.000681**	-0.001014***	-0.000200	-0.001029***	-0.001217***	-0.001009***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Containment measures (21 days lag)	-0.011812	-0.011802	-0.007546	0.001206	0.001201	0.000418	0.001791	0.001885
	(0.008)	(0.010)	(0.008)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Mobility (21 days lag)	0.000089**	0.000114**	0.000119***	-0.013693	-0.005394	-0.005564	-0.012225	-0.013662
	(0.000)	(0.000)	(0.000)	(0.012)	(0.005)	(0.008)	(0.009)	(0.010)
Lagged cases/pop	-0.003545*	0.002013	0.001909	0.000093**	0.000052*	0.000108**	0.000128***	0.000110***
	(0.002)	(0.003)	(0.004)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Constant	-2.078319	-1.915697	-1.935092	-1.368766	-6.560121***	-1.575337	4.209801*	-2.041791
	(1.468)	(1.353)	(1.250)	(1.617)	(1.913)	(1.455)	(2.464)	(1.400)
Observations	13,542	11,093	12,711	11,307	8,414	11,905	10,692	11,845
R-squared	0.587	0.605	0.597	0.609	0.782	0.605	0.598	0.608
Health policy controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of countries	126	90	119	104	88	108	100	104

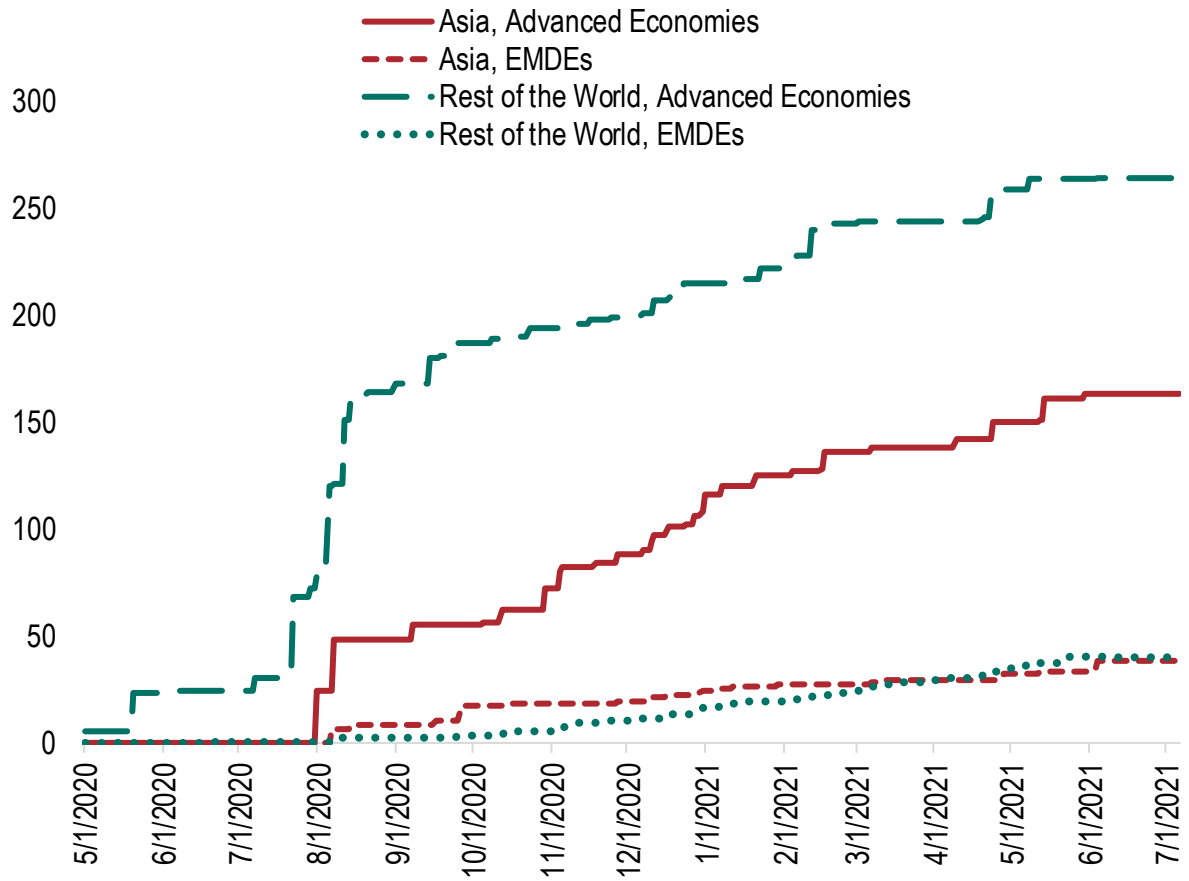
Notes: Table reports results for equation (2). The dependent variable is new COVID-19 cases per capita. Vaccine 1st dose per capita is lagged 21 days. The regressions control for stringency of containment measures, other non-pharmaceutical interventions and health policy controls (21 lags), lags of mobility (21 lags), lagged cases or reproduction rate, country specific time trends, as well as country and time fixed effects. Standard errors are clustered at the country level. ***, **, and * represent statistical significant at 1, 5 and 10 percent respectively.

Table A5. Effect of neighboring COVID-19 cases on domestic COVID-19 cases, using alternative weights

	(1)	(2)	(3)	(4)
	New COVID-19 Cases	New COVID-19 Cases	New COVID-19 Cases	New COVID-19 Cases
Vaccinated persons, 1 dose	-0.000930***	-0.000824***	-0.000818***	-0.000801***
	(0.000)	(0.000)	(0.000)	(0.000)
Vaccinated persons, 2 doses		-0.000282		-0.000051
		(0.000)		(0.000)
Neighbor cases (all capital cities, 7 days lag)	1.393726***	1.415165***		
	(0.521)	(0.520)		
Neighbor cases (trade weights, 7 days lag)			4.287295***	4.295574***
			(0.966)	(0.984)
COVID-19 cases (lag)	-0.001302	-0.001059	-0.000987	-0.000874
	(0.003)	(0.003)	(0.003)	(0.003)
Containment measures index (lag)	-0.009292	-0.010286	-0.008972	-0.009220
	(0.008)	(0.008)	(0.008)	(0.008)
Mobility (lag)	0.000106***	0.000111***	0.000102***	0.000105***
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	13,241	13,154	13,468	13,381
R-squared	0.635	0.635	0.634	0.634
Health Policy Controls	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
No. of countries	123	123	124	124

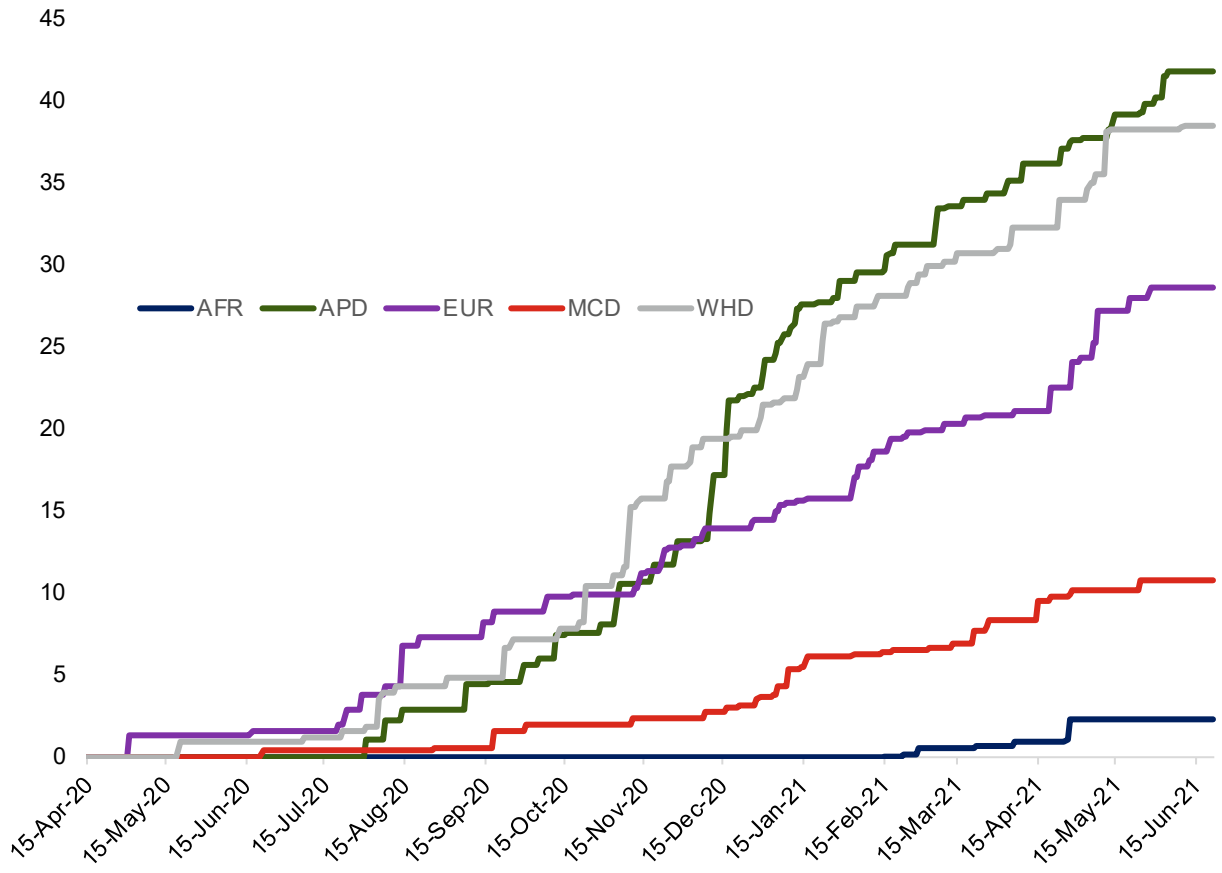
Note: Table reports results for equation (7). The dependent variable is new COVID-19 cases. A spillover term "Neighbor cases" (lag 7 days) is introduced to the equation to capture the effects of neighboring COVID-19 new cases on a country's own caseload using bilateral distance weights (equation 6). The regressions control for stringency of containment measures, other non-pharmaceutical interventions and health policy controls (21 lags), lags of mobility (21 lags), lagged new cases, country-specific time-trends, as well as country and time fixed-effects. Standard errors are clustered at the country level. ***, **, and * represent statistical significant at 1, 5 and 10 percent respectively.

Annex Figure A1. Vaccine Procurement Deals by Income Groups (weighted average, percent of the population to be vaccinated)



Note: countries are grouped per income level and weighted by population. Procurement deals include those already confirmed, potential deals, and donations. Source: Duke University Heath Innovation Center and author calculations.

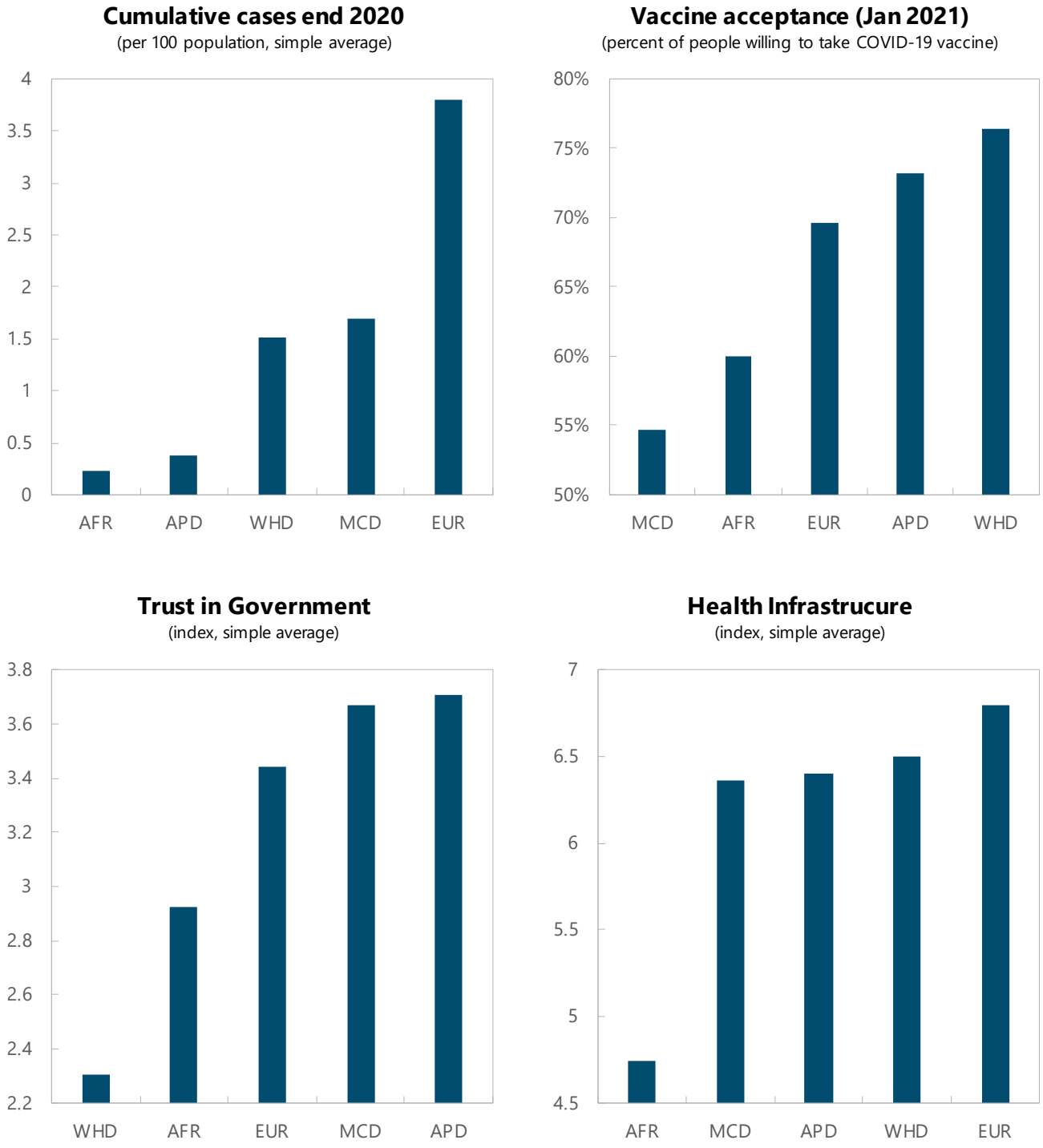
Annex Figure A2. Procurement per 100 population by region (orders, excluding potential orders)



Note: The chart includes confirmed orders, potential deals, and donations.

Source: Duke University Heath Innovation Center and author calculations.

Annex Figure A3. Determinants of vaccine rollout



Sources: Johns Hopkins University; University of Maryland and Global Competitiveness Report.