Global, regional, and national estimates of target population sizes for covid-19 vaccination: descriptive study

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ABSTRACT

OBJECTIVE
To provide global, regional, and national estimates of target population sizes for coronavirus disease 2019 (covid-19) vaccination to inform country specific immunisation strategies on a global scale.

DESIGN
Descriptive study.

SETTING
194 member states of the World Health Organization.

POPULATION
Target populations for covid-19 vaccination based on country specific characteristics and vaccine objectives (maintaining essential core societal services; reducing severe covid-19; reducing symptomatic infections and stopping virus transmission).

MAIN OUTCOME MEASURE
Size of target populations for covid-19 vaccination. Estimates use country specific data on population sizes stratified by occupation, age, risk factors for covid-19 severity, vaccine acceptance, and global vaccine production. These data were derived from a multipronged search of official websites, media sources, and academic journal articles.

RESULTS
Target population sizes for covid-19 vaccination vary markedly by vaccination goal and geographical region. Differences in demographic structure, presence of underlying conditions, and number of essential workers lead to highly variable estimates of target populations at regional and country levels. In particular, Europe has the highest share of essential workers (63.0 million, 8.9%) and people with underlying conditions (265.9 million, 37.4%); these two categories are essential in maintaining societal functions and reducing severe covid-19, respectively. In contrast, South East Asia has the highest share of healthy adults (777.5 million, 58.9%), a key target for reducing community transmission. Vaccine hesitancy will probably impact future covid-19 vaccination programmes; based on a literature review, 68.4% (95% confidence interval 64.2% to 72.6%) of the global population is willing to receive covid-19 vaccination. Therefore, the adult population willing to be vaccinated is estimated at 3.7 billion (95% confidence interval 3.2 to 4.1 billion).

CONCLUSIONS
The distribution of target groups at country and regional levels highlights the importance of designing an equitable and efficient plan for vaccine prioritisation and allocation. Each country should evaluate different strategies and allocation schemes based on local epidemiology, underlying population health, projections of available vaccine doses, and preference for vaccination strategies that favour direct or indirect benefits.

Introduction
As coronavirus disease 2019 (covid-19) continues to spread across the world, a total of 273 candidate vaccines for covid-19 are in development and twelve have entered phase III clinical trials as of 4 December 2020.1 Hopes are high to bring one or more vaccine candidates to the market by the end of the year. Despite 65.0 million cases reported so far,2 most of the world population still remains susceptible. Several seroepidemiological studies have reported low seroprevalence of antibodies to severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), in the range of 1.0-10.8%,3,4 although higher proportions have been reported locally (eg, approximately 20% in New York City, United States5). Therefore, a large demand for covid-19 vaccines is expected during the next year.

Twelve covid-19 vaccine manufacturers have announced their plans for vaccine production, with an estimated capacity of approximately 10 billion doses by the end of 2021.7-14 However, even in the highly optimistic scenario that 10 billion doses are effectively manufactured, with a two dose regimen (which is planned for most current covid-19 candidates), the existing annual production capacity14 is too limited to achieve herd immunity on a global scale (60-80% of the world population15). Therefore, defining priority groups for vaccination is necessary. Important

WHAT IS ALREADY KNOWN ON THIS TOPIC
Ethical frameworks to guarantee fair allocation of coronavirus disease 2019 (covid-19) vaccines globally have been described in previous studies
One of these studies also modelled optimal vaccine allocation strategies for different objectives using optimisation algorithms
Population sizes for covid-19 vaccination programmes targeting specific demographics, occupations, or high risk people (such as essential workers and those with pre-existing conditions) are needed

WHAT THIS STUDY ADDS
Target population sizes for covid-19 vaccination vary markedly by vaccination goal and geographical region
Owing to geographical heterogeneity, regional and country specific allocation strategies should be designed to maintain functional societies, minimise covid-19 burden, and reduce severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) transmission
Estimates of target population sizes can guide relevant stakeholders in the development of fair and equitable allocation strategies
questions remain about equitable and efficient distribution of covid-19 vaccines because many low and middle income countries lack covid-19 vaccine research, development, and production capacities. To ensure equitable access to covid-19 vaccines, COVAX (the vaccine pillar of the Access to Covid-19 Tools Accelerator) has been established, with global cooperation to ensure availability to higher and lower income countries. Additionally, because there will probably be an initial period of vaccine shortage, experts in the US and the United Kingdom have developed country specific interim frameworks for covid-19 vaccine allocation and distribution. However, information is lacking about the number of vaccine doses that each region and country needs, and this could hamper equitable and efficient allocation and distribution of covid-19 vaccines.

We used the allocation frameworks proposed by various international teams to provide global, regional, and national estimates of target population sizes for covid-19 vaccination by priority group. The vulnerability of each country to covid-19 is based on factors such as geographical location, disease burden, the likelihood of an outbreak, and the potential for severe covid-19 health impacts. Population groups can be categorised into different allocation tiers according to broad vaccine objectives. The three vaccine objectives that have been considered so far are (a) to maintain core societal functions, (b) to minimise deaths, and (c) to reduce transmission. Estimates of target population sizes based on these objectives can guide relevant stakeholders in the development of fair and equitable allocation strategies and inform local vaccination programmes.

Methods

Definition of target populations for covid-19 vaccination

We rely on previously proposed international allocation schemes for pandemic covid-19 vaccines that have endorsed three fundamental objectives (fig 1):

- To maintain essential core societal functions during the covid-19 pandemic, such as essential health services and food delivery
- To protect people from irreversible and devastating harm, such as death and severe covid-19 that causes long term organ damage (eg, lung, kidney, and liver)
- To control community transmission, enabling a return to baseline prepandemic economic and social activities.

The first vaccine allocation scheme targets essential workers, which extends beyond healthcare workers. Essential workers might include, but are not limited to, workers in the food industry and domestic transportation, police and military staff who maintain public safety, and workers who maintain electricity, water, fuel, information, and financial infrastructures.

The second vaccine allocation scheme targets people who might experience irreversible and devastating harm from covid-19 (that is, admission to hospital, admission to critical care, and death). Target populations include people older than 65 years, those with high risk health conditions, and those in close contact with people at very high risk of poor outcomes (eg, staff in nursing homes and long term care facilities). We considered people with the following underlying conditions: cardiovascular disease, chronic kidney disease, chronic respiratory disease, chronic liver disease, diabetes, cancer with direct immunosuppression, cancer without direct immunosuppression but with possible immunosuppression caused by treatment, HIV or AIDS, tuberculosis (excluding latent infections), chronic neurological disorders, and sickle cell disorders.

A third possible vaccine allocation scheme focuses on reducing SARS-CoV-2 transmission; in this case, high transmission groups should be targeted. Target populations include adults and children involved in economic or educational activities who experience higher risk of economic or educational harm from not working or going to school. These adults and children also have a higher probability of transmission when going back to work or school because of their large number of contacts. To reduce symptomatic infections and to stop virus transmission, vaccination should extend to all people younger than 60 years without any underlying conditions. These people can be further reclassified into three groups (aged 20-59 years, aged 5-19 years, and aged 0-4 years) on the basis of their risk of transmitting the virus, and projected economic harm from not working when considering the adult groups.

Because children have not been eligible to participate in phase III covid-19 vaccine trials conducted so far, first generation covid-19 vaccines are less likely to be licensed for children and this age group is unlikely to be prioritised for immunisation. Accordingly, all people younger than 20 years were excluded from the main analysis and reported only in a sensitivity analysis to provide a fuller picture of target population sizes across the globe.

Data sources

To estimate the size of the priority groups for vaccination by country, we extracted country specific information from the following publicly available sources covering the period 2013-20 (table S1):
Fig 1 | Priority groups for covid-19 vaccination. Covid-19=coronavirus disease 2019; SARS-CoV-2=severe acute respiratory syndrome coronavirus 2
covering 1.3 billion people, representing 16.5% of the world population) or we used non-official sources for numbers of police and military staff (n=49, about 1.4 billion people, 18.2% of the world population). However, police and military staff in those 49 countries account for only 0.03-1.1% of the total population of each country, and therefore have a limited impact on global and regional estimates of target populations.

To avoid overlap between the essential workers group and adults aged 20-59 years without any underlying conditions, we subtracted those engaging in essential work activities from the broader group of healthy adults. Additionally, data on age specific prevalence of underlying conditions were lacking for 11 countries. In the main analysis, we assumed that the age specific prevalence of underlying conditions in countries with missing data was the same as the WHO regional average. Then, the number of people with and without underlying conditions at a given age is equal to the prevalence of underlying conditions multiplied by the corresponding population size. The appendix reports a sensitivity analysis in which we assume that the number of people without any underlying conditions corresponds to the total number of people of that age, if no data exist.

In a sensitivity analysis, we considered the possibility that countries might want to exclude people who have a history of SARS-CoV-2 vaccination from priority groups. Therefore, we collected data on the number of people with covid-19 as of 10 November 2020 and examined serology surveys. We found data on the number of people who tested positive for SARS-CoV-2 by reverse transcription polymerase chain reaction (n=182 countries) or serological assays (n=63) from 1.4 billion people, 18.2% of the world population) or we used non-official sources for numbers of police and military staff (n=49, about 1.4 billion people, 18.2% of the world population). However, police and military staff in those 49 countries account for only 0.03-1.1% of the total population of each country, and therefore have a limited impact on global and regional estimates of target populations.

By analysing and modelling national, regional, and country specific data on occupation, demography, and health conditions, we can parse out the total population in different priority groups based on three main vaccination objectives. If vaccines are preferentially allocated to priority workers to help maintain societal functions, the global target population is 258.3 million people (fig 2). If young children (0-4 years) and school aged children and young people (5-19 years) were not initially prioritised or eligible for vaccination, the target population would be 5.2 billion people (95% confidence interval 5.1 to 5.2 billion; table 1).

Fig 2 | Global estimates of target population sizes for covid-19 vaccination by goal of vaccination programmes. Covid-19=coronavirus disease 2019

### Vaccine coverage: 60-80%

### No of people (millions)

<table>
<thead>
<tr>
<th>Goal</th>
<th>Healthcare workers</th>
<th>Police and military</th>
<th>Other essential workers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>People aged ≥60 years with at least one underlying condition</td>
<td>People aged ≥60 years without any underlying conditions</td>
<td>People aged &lt;60 years with at least one underlying condition</td>
</tr>
<tr>
<td>2</td>
<td>People aged 60-79 years without any underlying conditions</td>
<td>People aged 60-79 years with at least one underlying condition</td>
<td>People aged &lt;60 years without any underlying conditions</td>
</tr>
<tr>
<td>3</td>
<td>Healthy adults (20-59 years)</td>
<td>School aged children and young people (5-19 years)</td>
<td>Young children (0-4 years)</td>
</tr>
</tbody>
</table>

### Estimates of willingness to accept a covid-19 vaccine

To estimate the willingness of the population to accept a covid-19 vaccine, we performed a systematic review and meta-analysis. We queried PubMed, Embase, Web of Science, and MedRxiv using the following terms: “COVID-19 AND (accept* OR hesitancy OR attitude OR preference).” We identified 30 relevant studies (fig S1). We then used random effects models to estimate the acceptance rate on national and regional scales. For countries without reports on the acceptance of a covid-19 vaccination, the acceptance rate was assumed to be the same as the WHO regional average.

### Estimates of covid-19 vaccine production capacity

We searched the web for information on the expected production capacity of major pharmaceutical companies currently running phase III vaccination trials. We retrieved information from 12 companies (table S9) and summed the reported capacities to obtain an upper bound estimate of the vaccine production capacity, standing at around 10 billion doses by the end of 2021. However, this figure is probably an overestimate because it does not account for the following factors: some vaccine candidates might not be licensed by the end of 2021, some might be dropped owing to lack of effectiveness, and production chains could suffer unexpected delays.

### Patient and public involvement

This research did not involve consultation with patients or the public.

### Results

#### Global prospective

We start by evaluating the full scope of a universal vaccine programme that does not have priority groups. The global target population would be 7.8 billion people (fig 2). If young children (0-4 years) and school aged children and young people (5-19 years) were not initially prioritised or eligible for vaccination, the target population would be 5.2 billion people (95% confidence interval 5.1 to 5.2 billion; table 1).

By analysing and modelling national, regional, and country specific data on occupation, demography, and health conditions, we can parse out the total population in different priority groups based on three main vaccination objectives. If vaccines are preferentially allocated to priority workers to help maintain societal functions, the global target population is 258.3 million people.
(95% confidence interval 241.7 to 279.7 million), including 40.7 million (15.8%) healthcare workers, 46.9 million (18.2%) police and military, and 170.7 million (66.1%; 95% confidence interval 154.1 to 192.1 million; 63.8% to 68.7%) people who have experienced a natural SARS-CoV-2 infection who might not be considered as a priority for vaccination, as they have not been recruited in any phase III clinical trials of a COVID-19 vaccine to date.

We emphasise that any vaccination programme is likely to vary considerably by region. Highest concentrations are in the Americas (1.5 billion, 28.2%) together with the Western Pacific (1.5 billion, 28.2%) and the Eastern Mediterranean (0.4 billion, 7.4%). The estimated size of the target population groups across WHO regions. If we consider the target for vaccination is the entire population (no prioritisation by occupation or risk group), South East Asia (1.3 billion, 25.5%) and the Western Pacific (1.5 billion, 28.2%) together account for 53.7% of the population to vaccinate. The target populations across other regions are 10.4% for Africa (0.5 billion), 13.9% for the Americas (0.7 billion), 13.8% for Europe (0.7 billion), and 8.2% for the Eastern Mediterranean (0.4 billion; table 1). Similarly, the size of the target population to maintain essential societal functions varies considerably by region. Highest concentrations are in Europe (63.0 million people, 24.4%), the Western

### Table 1 | Estimates of target population sizes for COVID-19 vaccination by goal of vaccination programme

<table>
<thead>
<tr>
<th>All</th>
<th>Africa</th>
<th>Americas</th>
<th>Eastern Mediterranean</th>
<th>Europe</th>
<th>Western Pacific</th>
<th>South East Asia</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maintaining essential core societal services</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
<td>258.3</td>
<td>(241.7 to 279.7)</td>
<td>25.4</td>
<td>44.5</td>
<td>31.9</td>
<td>63.0</td>
</tr>
<tr>
<td>Healthcare workers</td>
<td>40.7</td>
<td>1.4</td>
<td>10.9</td>
<td>1.8</td>
<td>10.8</td>
<td>10.6</td>
</tr>
<tr>
<td>Police and military*</td>
<td>46.9</td>
<td>3.2</td>
<td>8.0</td>
<td>6.1</td>
<td>8.4</td>
<td>10.7</td>
</tr>
<tr>
<td>Other occupational population</td>
<td>170.7</td>
<td>(154.1 to 192.1)</td>
<td>20.7</td>
<td>25.6</td>
<td>24.0</td>
<td>43.8</td>
</tr>
<tr>
<td><strong>Reducing severe COVID-19</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
<td>2145.0</td>
<td>206.3</td>
<td>301.9</td>
<td>158.2</td>
<td>345.7</td>
<td>626.2</td>
</tr>
<tr>
<td>People aged ≥60 years with at least one underlying condition</td>
<td>657.6</td>
<td>35.8</td>
<td>113.1</td>
<td>35.9</td>
<td>144.8</td>
<td>197.9</td>
</tr>
<tr>
<td>People aged ≥80 years without any underlying conditions</td>
<td>28.6</td>
<td>0.8</td>
<td>4.5</td>
<td>0.8</td>
<td>7.3</td>
<td>10.8</td>
</tr>
<tr>
<td>People aged 60-79 years without any underlying conditions</td>
<td>354.1</td>
<td>19.0</td>
<td>51.2</td>
<td>15.8</td>
<td>61.5</td>
<td>132.0</td>
</tr>
<tr>
<td>People aged 20-59 years with at least one underlying condition</td>
<td>962.7</td>
<td>111.6</td>
<td>118.2</td>
<td>87.0</td>
<td>121.1</td>
<td>262.8</td>
</tr>
<tr>
<td>Pregnant women</td>
<td>142.0</td>
<td>39.1</td>
<td>14.9</td>
<td>18.7</td>
<td>11.0</td>
<td>22.7</td>
</tr>
<tr>
<td><strong>Reducing symptomatic infections and stopping virus transmission†</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
<td>2761.0</td>
<td>(2739.6 to 2777.6)</td>
<td>304.2</td>
<td>373.1</td>
<td>231.6</td>
<td>303.0</td>
</tr>
<tr>
<td>Adults without conditions</td>
<td>2761.0</td>
<td>(2739.6 to 2777.6)</td>
<td>304.2</td>
<td>373.1</td>
<td>231.6</td>
<td>303.0</td>
</tr>
<tr>
<td>Adults with conditions</td>
<td>2761.0</td>
<td>(2739.6 to 2777.6)</td>
<td>304.2</td>
<td>373.1</td>
<td>231.6</td>
<td>303.0</td>
</tr>
<tr>
<td>Total</td>
<td>5164.3</td>
<td>(5126.3 to 5202.3)</td>
<td>535.9</td>
<td>719.4</td>
<td>421.6</td>
<td>711.7</td>
</tr>
</tbody>
</table>

Covid-19 coronavirus disease 2019. Data are presented as means (95% confidence intervals) by using bootstrap method.

*Estimated number of people is based on 149 countries with available data.
†Children and young people (aged 0-19) were not directly prioritised as a target population because they have not been recruited in any phase III clinical trials of a COVID-19 vaccine to date.
Pacific (58.8 million people, 22.8%), and the Americas (44.5 million people, 17.2%; table 1 and fig 3, fig 4, fig 5). The size of the population at high risk of severe covid-19 and those to vaccinate to contain covid-19 are highest in the Western Pacific (1.4 billion) and South East Asia (1.3 billion).

The size of age specific target population groups also varies markedly across regions. Few people are older than 80 years in Africa while a considerable proportion live in Europe and North America (fig S2). The working age population accounts for a substantially larger proportion of the total population than other target populations in all regions. Additionally, the proportion of people younger than 20 years is relatively high in Africa compared with other regions (fig S2).

If people with a history of SARS-CoV-2 infection are excluded from vaccine priority groups, regional differences become more accentuated. The largest decrease in the number of doses needed is found in Europe relative to the base scenario (table S4).

**National perspectives**

Here we focus on 104 countries with high quality data collected from official reports, covering 74.4% (5.8 billion) of the world population. Sizable heterogeneity emerges in the distribution of different target population groups, ranging from 1000 to 1.4 billion people (figs S3, S4 and table S7). National estimates of the size of target populations suggest that six countries—China, India, the US, Pakistan, Brazil, and Nigeria—have the largest share of the total target population (fig 6 and figs S3, S4). In contrast, countries in Africa and the Eastern Mediterranean account for a relatively low share (figs S5, S6 and figs S7, S8).

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**Table 2 | Estimates of target population sizes for covid-19 vaccination in 194 countries, assuming vaccination coverage of 60% and 80%**

<table>
<thead>
<tr>
<th>Vaccination and goals of vaccination</th>
<th>60%</th>
<th>80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHO region (millions)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Americas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eastern Mediterranean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Pacific</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South East Asia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintaining essential core societal services</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
<td>1287.0</td>
<td>1656.6</td>
</tr>
<tr>
<td>Healthcare workers</td>
<td>394.6</td>
<td>155.0</td>
</tr>
<tr>
<td>Police and military*</td>
<td>577.6</td>
<td>432.6</td>
</tr>
<tr>
<td>Other occupational population</td>
<td>85.2</td>
<td>136.6</td>
</tr>
<tr>
<td>Reducing severe covid-19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
<td>155.0</td>
<td>155.0</td>
</tr>
<tr>
<td>People aged 60+ years with at least one underlying condition</td>
<td>394.6</td>
<td>394.6</td>
</tr>
<tr>
<td>People aged 80+ years without any underlying conditions</td>
<td>17.2</td>
<td>17.2</td>
</tr>
<tr>
<td>People aged 60-79 years without any underlying conditions</td>
<td>212.5</td>
<td>212.5</td>
</tr>
<tr>
<td>People aged 20-59 years with at least one underlying condition</td>
<td>375.7</td>
<td>375.7</td>
</tr>
<tr>
<td>Pregnant women</td>
<td>85.2</td>
<td>85.2</td>
</tr>
<tr>
<td>Reducing symptomatic infections and stopping virus transmission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
<td>1287.0</td>
<td>1656.6</td>
</tr>
<tr>
<td>Adults without conditions</td>
<td>394.6</td>
<td>394.6</td>
</tr>
<tr>
<td>People aged 60+ years with at least one underlying condition</td>
<td>577.6</td>
<td>577.6</td>
</tr>
<tr>
<td>People aged 80+ years without any underlying conditions</td>
<td>85.2</td>
<td>85.2</td>
</tr>
<tr>
<td>People aged 60-79 years without any underlying conditions</td>
<td>212.5</td>
<td>212.5</td>
</tr>
<tr>
<td>People aged 20-59 years with at least one underlying condition</td>
<td>375.7</td>
<td>375.7</td>
</tr>
<tr>
<td>Pregnant women</td>
<td>85.2</td>
<td>85.2</td>
</tr>
<tr>
<td>Total</td>
<td>2208.8</td>
<td>2208.8</td>
</tr>
</tbody>
</table>


*Estimated number of people is based on 149 countries with available data.

†Children and young people (aged 0-19) were not directly prioritised as a target population because they have not been recruited in any phase III clinical trials of a covid-19 vaccine to date.

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When we consider country specific willingness to be vaccinated, geographical disparities in the distribution of target population sizes do not substantially change (table S8). We also found that the target population that maintains essential core societal function, based on our definition, is more predominant in middle and high income countries (fig 6 and fig S7). Moreover, we observed between country variations in the size of the target population to reduce severe disease or to contain SARS-CoV-2 transmission, with 14.1% (1.1 billion) and 30.1% (2.3 billion), respectively, of the total world population found in China, India, the US, Japan, and Brazil (fig 6, fig S8).

For the 11 countries lacking data on age specific prevalence of underlying conditions, our estimates of the target populations were robust to changes in modelling assumptions (table S4).

Discussion
We identified target population groups according to three different goals of covid-19 vaccination programmes aimed at maintaining essential societal functions, minimising severe disease, and interrupting transmission. We quantified the size of each target group on a global, regional, and country level. Important variations were observed in the amount of vaccines needed depending on the goals of the vaccination programme, and the distribution of target populations was found to vary within and between regions. In particular, we estimate the demand for vaccines would be high for essential workers and high risk populations with health conditions, with the second group accounting for 27.7% (2.2 billion) of the total world population.

Implications of findings
By assuming a two dose vaccine schedule, we estimate that approximately 15.6 billion doses of covid-19 vaccines will be required by the 194 WHO member states for a universal covid-19 vaccination programme (table S4), and 10.3 billion for targeted occupational or high risk groups. Twelve covid-19 vaccine manufacturers have announced that about 10 billion doses will be available by the end of 2021 (table S9). In the most optimistic scenario that this figure is actually reached, it would take about six to seven months to produce enough vaccines to achieve herd immunity by protecting at least 60-80% of the world population (4.7-6.2 billion). Even if manufacture of candidate vaccines is going smoothly, this is just the first step in a long process to deliver vaccines to populations, and other monumental challenges will be faced (eg,
logistics, cold chain, and administration of vaccines). International and national supply chains will probably limit the worldwide and nationwide distribution of covid-19 vaccines. WHO reports that vaccine wastage amounts to approximately 50% every year, often because of inadequate temperature control of the supply chains. Therefore, substantial investment is needed to strengthen international and national supply chains, especially to guarantee the distribution of vaccines in rural and remote communities in many developing countries.

A sufficient level of vaccine acceptance in any given country or region will be needed to reach herd immunity and prevent community spread of SARS-CoV-2. As exemplified by other vaccine preventable diseases (eg, the 2019 measles outbreak in the US), vaccine hesitancy could hamper the beneficial effects of vaccination campaigns. Based on our meta-analysis of recent surveys, an estimated 68.4% (95% confidence interval 64.2% to 72.6%) of the world population is willing to receive covid-19 vaccination, although this estimate will probably change over time as incidence increases or decreases. Although our meta-analysis highlighted regional differences in acceptance of covid-19 vaccines, these differences did not substantially influence our estimates on a regional level. However, such differences could play a larger role on a national (or subnational) scale.

In a scenario of limited vaccine availability at the beginning of a covid-19 vaccination programme, the same barriers would apply to all target groups, but vaccination of targeted occupational or high risk groups will probably be more feasible than the general public without any underlying conditions. These groups together comprise an estimated 2.5 billion people in the 194 WHO member states. Disparities in availability and distribution of covid-19 vaccine within and between regions should also be borne in mind. These disparities will result in different durations of vaccination programmes owing to global limitations in vaccine production, supply capacity, and market forces. For example, in countries with sufficient local capacity for vaccine production and supply to meet the national demand (eg, the US and China), vaccination of a substantial proportion of priority groups could be achieved in a few months. However, the process could last much longer in low and middle income countries, which have lower capacity to secure and deliver vaccines. Ongoing challenges remain in bringing a covid-19 vaccine to the market alongside endorsements of needs based allocation principles. One of the biggest challenges is the lack of a procedural governance mechanism to enforce these allocation principles on a global level. To a large extent, access to the vaccine will be determined by market mechanisms and altruism rather than central planning. Therefore, as efforts to bring covid-19 vaccines to the market progress, international institutions, national governments, and manufacturers need to work out vaccine allocation plans and negotiate affordable prices.

In addition to the direct benefits of vaccination (protection of vaccinated people from infection, reduction in illnesses, and mortality rates), prioritisation should also balance the indirect benefits of a vaccine programme that reduces virus circulation in a community because vaccinated people are less likely to be infected and transmit the virus. In particular,
indirect benefits might be important to protect people older than 65 years who are at increased risk of severe disease and also possibly less likely to be directly protected by vaccination because of immune senescence. Therefore, the effectiveness of different vaccine candidates against infection, severe disease, and transmission should be considered when designing a vaccination programme if several vaccines maintain essential core societal services.

Fig 6 | Estimates of target population sizes for covid-19 vaccination programmes in 104 countries with robust data on occupation and high risk groups by goal of vaccination programme. Upper panel: target populations to maintain essential core societal services; middle panel: target populations to reduce severe covid-19; lower panel: target populations to reduce symptomatic infections and stop virus transmission. Empty cells represent lack of data on target populations. Covid-19=coronavirus disease 2019
become available concomitantly. For instance, a highly effective vaccine against severe disease could be administered to shield essential workers and the most vulnerable groups, maintain a functional society, and lower covid-19 burden. At the same time, a less effective vaccine against infection could still be distributed to the general adult population and might contribute to reaching the herd immunity threshold.

We were unable to collect data on population stratified by occupation in 25.8% (n=50) of the countries considered. Excluding these data from the analysis would lead to the exclusion of a substantial proportion of the total population (around 0.86 billion people, 11%), and would make it difficult to understand global heterogeneity in the distribution of each target population. Therefore, we included these countries in regional and global estimates, and used an imputation algorithm. Unlike other approaches that use values imputed from average numbers, however, this algorithm considers uncertainty in the missing values by creating several different plausible imputed datasets from their predictive distribution (based on the observed data). Variability between the imputed datasets can be considered, and average estimates can be obtained. This approach gives more robust estimates of the size of the target populations on local, regional, and global scales.

Limitations of study
A few limitations of the study should be highlighted. Firstly, lack of timely data for 2020 constrains estimates of population sizes in many countries. However, the distribution of target occupational and high risk groups is probably stable over a few years. Secondly, we could not explore variations in target populations within countries. Policy makers should investigate and discuss actual vaccine allocation plans when more local data become available in their country. Thirdly, owing to unavailability of data, we were not able to provide estimates of the size of the target population among other essential workers (e.g., people working in the finance and economy sector) or estimate target population sizes by other demographic factors, such as racial and ethnic groups, which are reported to target population sizes by other demographic factors, such as racial and ethnic groups, which are reported to

Conclusions and policy implications
Findings from this study provide an evidence base for global, regional, and national vaccine prioritisation and allocation. Variations in the size of the target populations within and between regions emphasise the tenuous balance between vaccine demand and supply, especially in low and middle income countries without sufficient capacity to meet domestic demand for covid-19 vaccine. This study presents a strategy for vaccine allocation based on three main goals, which should be considered as a general framework when discussing and evaluating plans. Other additional factors such as availability of vaccines for initial distribution, epidemiological situation, and vaccine hesitancy should be taken into account by individual countries to refine allocation plans.

Contributors: WW, QW, and HY had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. CV, MA, and HY were responsible for its conception and design. WW, QW, KD, XingC, XB, XinH, and ZL were responsible for the acquisition, analysis, or interpretation of data. WW, QW, JY, CV, MA, and HY drafted the manuscript. JY, CV, MA, and HY made critical revision of the manuscript for important intellectual content. WW, QW, XingC, and XB did the data analysis. JY, CV, and MA provided administrative, technical, or material support. CV, MA, and

doi: 10.1136/bmj.m4704 | BMJ/2020;371:m4704 | thebmj

BMJ: first published as 10.1136/bmj.m4704 on 15 December 2020. Downloaded from http://www.bmj.com on 6 July 2023 by guest. Protected by copyright.
HY are joint senior authors and contributed equally to this work. HY is the guarantor. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

Funding: The study was funded by the National Science Fund for Distinguished Young Scholars (No 81572053), Key Emergency Project of Shanghai Science and Technology Committee (No 202011950100), and National Science and Technology Major Project of China (No 2018ZX1013001-007, No 2017ZX10103009-005, No 2018ZX10201001-010). The funders had no role in the design and conduct of the study, collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Competing interests: All authors have completed the ICMJE uniform disclosure form at www.icmje.org/coiDisclosure.pdf and declare: support from the National Science Fund for Distinguished Young Scholars, Key Emergency Project of Shanghai Science and Technology Major Project of China for the submitted work; MA has received research funding from Seqirus and HY has received research funding from Sanofi Pasteur, GlaxoSmithKline, Yichang HEC Changjiang Pharmaceutical Company, and Shanghai Roche Pharmaceutical Company. None of those research fundings related to covid-19. All other authors report no competing interests.

Ethical approval: Not required.

Data sharing: The datasets used and analysed during the current study are available in appendix.

The lead author affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned have been explained.

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Web appendix: Appendix