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Article

Percentages of Vaccination Coverage Required To Establish Herd Immunity Against SARS-Cov-2

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Abstract: The pandemic associated with SARS-CoV-2 is a worldwide public health challenge. The WHO has proposed to achieve 70% COVID-19 vaccination coverage in all countries by mid-2022. Nevertheless, the prevention strategy based on COVID-19 vaccination and other applied prevention measures have not been sufficient to prevent SARS-CoV-2 epidemic waves. The study assessed the vaccination coverage that would be required to establish herd immunity against SARS-CoV-2 by taking into account virus transmissibility (R_o values from 1.1 to 10) and Covid-19 vaccination effectiveness. The study found that Covid-19 vaccination programs could establish herd immunity against SARS-CoV-2 with $R_o < 3$ with levels of Covid-19 vaccination effectiveness of 10−100% and against viruses with R_o values ranging from 3 to 10 with levels of Covid-19 vaccination effectiveness of 70−100%. Factors reducing Covid-19 vaccination effectiveness (emergent variants, infections among vaccinated inidividuals, high risk individuals) and factors increasing SARS-CoV-2 transmissibility (close settings) increased percentages of vaccination coverage that would be required to establish herd immunity. The vaccination coverage objective of 70% could be adequate against SARS-CoV-2 with R_o values of 1.1−2.5, while percentages of vaccination coverage of 80% and 90% could be more adequate against viruses with R_o values of 2.5−3.5 and >3.5, respectively. Covid-19 vaccines should achieve higher levels of effectiveness in preventing Omicron infection to block SARS-CoV-2 transmission in the community. Percentages of Covid-19 vaccination coverage should be increased in most countries of the world in order to increase individual and herd immunity protection.

Keywords: Covid-19 vaccination coverage; anti-SARS-CoV-2 herd immunity; Covid-19 vaccination strategy; SARS-CoV-2

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1. Introduction

The World Health Organization (WHO), on March 11, 2020, declared the coronavirus disease 2019 (Covid-19) epidemic caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) a global pandemic [1]. This pandemic dates to December 2019, when a cluster of unexplained pneumonia cases was identified in Wuhan (China) [2]. Despite global efforts have been made during the last two years to mitigate the pandemic, SARS-CoV-2 continues to spread around the world. Globally, as of 18 April, 2022, 500.2 million laboratory confirmed cases of SARS-CoV-2 infection have been reported, resulting in 6.2 million deaths [3]. The number of cases reported in last 24 hours were 948,845 [3].

The pandemic associated with SARS-CoV-2 is a worldwide public health challenge. The prevention strategy implemented to reduce transmission of SARS-CoV-2 and mitigate pandemic health and economic effects included: 1) measures to detect infected individuals,

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2) measures to treat Covid-19, 3) measures to prevent SARS-CoV-2 infections and Covid-19, and 4) measures to reduce exposition to SARS-CoV-2.

Vaccination is the primary method for preventing and controlling SARS-CoV-2 pandemic. Covid-19 vaccination programs can reduce the incidence and mortality from SARS-CoV-2 infections by means of individual protection in vaccinated individuals and herd immunity protection in unvaccinated individuals. As of 10 April, 2022, 11.37 million doses had been administered in the world, 58.2% of the word population had completed Covid-19 vaccination and 64.7% had received at least one dose of vaccine [4]. The coverage for completed vaccination was 58.2% in the World, 73.2% in South America, 67.7% in Asia, 65.3% in Europe, 62.9% in Oceania, 62.7% in North America, and 15.4% in Africa [4]. Percentages of fully vaccination coverage ranged from 0.1% in Burundi to 96.3% in United Arab Emirates [4] (Supplement Table 1).

On April 2022, nine vaccines had been validated for use by WHO after receiving emergency use authorizations: Pfizer/BioNTech, Moderna, AstraZeneca. Janssen, Sinopharm BIBP, Sinovac, CoronaVac, Covaxin and Novavax [5] (Table 1). Five vaccines have been authorised by the European Medicines Agency (EMA): Pfizer/BioNTech, Moderna, AstraZeneca. Janssen and Novavax [5]. Five vaccines are under assessment by the WHO: Sputnik, Sinopharm WIBP, Convidecia, Sanofi–GSK and SCB-2019 [5]. Available vaccines have been developed using different technologies, including mRNA, virus vector and adjuvanted recombinant protein nanoparticles [5]. There are more than 300 vaccine candidates, 143 vaccines in different clinical stages of development and 195 vaccines undergoing pre-clinical development [6].

Covid-19 vaccines are associated with high anti-SARS-CoV-2 immunity levels and reductions in morbidity and mortality from Covid-19 [7,8]. The effectiveness of available vaccines in preventing severe disease ranged from 37% to 73% for the Omicron variant and from 49% to 97% for the Delta variant, and the effectiveness in preventing infections ranged from 49% to 97% for the Omicron variant and from 46% to 92% for the Delta variant [8] (Table 1). The effectiveness in preventing severe Omicron infection was 71–73% using Astra/Zeneca, Moderna and Pfizer/BioNTech vaccines, 57–67% using Sputnik, Janssen, Novavax and Covaxin, vaccines and 37–53% using other vaccines [8] (Table 1).

Table 1. Effectiveness for available Covid-19 vaccines. Data from the Institute for Health Metrics and Evaluation (IHME) [4].

	Effectiveness (%) in preventing					
	Ancetral variant		Delta variant		Omicron variant	
Vaccine	Severe disease	Infection	Severe disease	Infection	Severe disease	Infection
Moderna	97	92	97	91	73	48
Pfizer/BioNTech	95	86	95	84	72	44
Sputnik	92	86	89	85	67	44
Novavax	89	83	86	82	65	43
Covaxin	78	73	76	72	57	38
Oxford/Astra-Zeneca	94	63	94	69	71	36
Sinopharm	73	68	71	67	53	35
Janssen	86	72	76	64	57	33
CoronaVac	50	47	49	46	37	24

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Convidecia	66	62	64	61	48	22

The WHO has proposed to achieve 70% COVID-19 vaccination coverage in all countries by mid-2022 [9]. It was expected that achieving 60–90% vaccination coverage could generate sufficient herd immunity to block transmission of SARS-CoV-2 in the population [10]. Nevertheless, in 2022, the fully vaccination coverage was at least 70% in 27% of the countries of the world, and intensive prevention measures implemented since 2020 have not been sufficient to prevent SARS-CoV-2 epidemic waves [4].

Several factors could explain the persistence of SARS-CoV-2 in the world. First, percentages of vaccination coverage achieved could not be sufficient to block transmission SARS-CoV-2 in the community and in different population groups. Second, emergence of SARS-CoV-2 variants could scape vaccine-induced immunity protection and natural immunity protection generated by previous variants. Recent studies suggest that the spread of Omicron variant is associated with lower Covid-19 vaccination effectiveness [11,12]. Third, waning vaccine-induced immunity could make it difficult to reach and maintain herd immunity in the population [13,14]. Fourth, lack of sufficient vaccination coverage among children and infants could not prevent transmission of SARS-CoV-2 infections to children and infants [15,16].

The questions are therefore: What are the percentages of Covid-19 vaccination coverage required to establish herd immunity against different SARS-CoV-2 in the population? Is the Covid-19 vaccination coverage objective of 70% sufficient to establish herd immunity against SARS-CoV-2. What are the effects of infections among vaccinated individuals and wanning immunity protection on percentages of vaccination coverage that would be required to establish herd immunity?

The objectives of this study were: 1) To determine percentages of Covid-19 vaccination coverage required to establish herd immunity against different SARS-CoV-2. 2) To assess the effect of Omicron-associated reinfections among vaccinated individuals on percentages of vaccination coverage required to establish herd immunity. 3) To assess whether the WHO Covid-19 vaccination coverage objective of 70% and alternative objectives of 80% and 90% are sufficient to establish herd immunity against different SARS-CoV-2. 4) To assess the vaccination coverage required to establish herd immunity in populations with individuals already protected against SARS-CoV-2 due to natural infection.

2. Materials and Methods

2.1. Herd immunity against SARS-CoV-2

Herd immunity against SARS-CoV-2 viruses is defined as the indirect protection of susceptible individuals generated by a prevalence of protected individuals (I). Herd immunity is established in a population when the prevalence of immune or protected individuals is higher than the critical prevalence “herd immunity threshold” ($I > I_c$) [17–21]. When this occurs, transmission of SARS-CoV-2 viruses is blocked because the number of susceptible individuals infected per case is lower than 1. By contrast, when the prevalence of protected individuals is lower than the herd immunity threshold, the number of susceptible individuals infected per case is higher than 1, and infections grows exponentially spreading the coronavirus disease in the community. For this reason, the objective of Covid-19 vaccination programs should be to achieve and maintain a prevalence of protected individuals in the community higher than the critical prevalence [10].

The establishment of herd immunity against SARS-CoV-2 in a community depends on community and viral factors. Transmissibility of SARS-CoV-2 can be measured by the basic reproductive number, R_o, that indicates the number of secondary cases generated by one primary case in a totally susceptible population. The basic reproduction number R_o is a key parameter explaining Covid-19 epidemic dynamics because the herd immunity threshold depends on the virus-specific basic reproductive number R_o.

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In a totally susceptible population, each infected case will generate R_o new cases, but the prevalence of susceptible individuals will decrease over time reducing the R_o value to an effective basic reproduction number, R, depending on the prevalence of susceptible individuals (S) and the prevalence of protected individuals (I):

$$R = R_o S = R_o (1 - I). \tag{1}$$

The herd immunity threshold in terms of critical prevalence of protected individuals required to establish herd immunity against SARS-CoV-2 can be determined using the formula:

$$I_c = 1 - (1/R_o). \tag{2}$$

In this study, the prevalence of protected individuals required to establish herd immunity against SARS-CoV-2 was determined assuming that SARS-CoV-2 can be associated with basic reproduction numbers R_o ranging from 1.1 to 10 [22–26].

Transmissibility of SARS-CoV-2 measured by R_o values has increased since the beginning of the pandemic in China. R_o values ranging from 0.32 to 6.47 were obtained on January-April 2020, with R_o values ranging from 3.6 to 4.5 in Wuham city, from 0.47 to 6.47 in different regions of China, and from 1.27 to 5 in different countries [22]. R_o values ranging from 1.4 to 6.49, with a mean of 3.28, were obtained in a review of articles published on January-February 2020 [23]. Recent analysis have obtained R_o values ranging from 3.2 to 8, with a mean of 5.08, for Delta variant [24]. A study carried out in Denmark found that transmissibility could be 3.19 (95% CI: 2.82–3.61) times greater for Omicron than for Delta infections under the same epidemiological conditions [25,26]. It is possible to assume that R_o values of SARS-CoV-2 ranged from 1.1 to 5 during 2020 and from 3 to 10 since 2020.

2.2. Vaccination coverage required to establish herd immunity against SARS-CoV-2

Covid-19 vaccination programs can establish herd immunity when the prevalence of vaccine-induced protected individuals is equal to or higher than the herd immunity threshold ($I_v \geq I_c$) [20,21]. In this situation, the average number of infected individuals generated per each infected case is lower than 1, and transmission of SARS-CoV-2 is blocked in the population.

Covid-19 vaccination programs establish anti-SARS-CoV-2 herd immunity when the prevalence of vaccine-induced protected individuals, which depends on the vaccination coverage and vaccine effectiveness, is at least equal to the critical prevalence I_c. For this reason, the critical vaccination coverage (V_c) required to establish herd immunity against SARS-CoV-2 was determined by dividing the herd immunity threshold (I_c) by the level of vaccine effectiveness (E):

$$V_c = I_c/E = [1 - (1/R_o)]/E. \tag{4}$$

This method is based on the following assumptions: 1) homogeneous mixing of individuals within the population, 2) homogeneous distribution of infected and vaccine-induced protected individuals within the population, and 3) fully susceptible population [17–21].

In this study, the critical vaccination coverage was determined using Formula (4) for SARS-CoV-2 with R_o values ranging from 1.1 to 10 [22–26], and for levels of vaccination effectiveness in preventing SARS-CoV-2 infections ranging from 10% to 100%.

Available Covid-19 vaccines are effective in preventing SARS-Cov-2 infections, severe disease and morttality from Covid-19 [7,8,27–28]. The effectiveness of Covid-19 vaccines in preventing SARS-CoV-2 infection ranged from 24% to 48% for Omicron infection and from 46% to 91% for Delta infection, the effectiveness in preventing severe Omicron disease ranged from 48% to 73% and the effectiveness in preventing Delta severe ranged from 49% to 95% [8] (Table 1).

Required percentages of vaccination coverage that would be required to establish herd immunity are higher in close settings (schools, nursing homes and health care centers) than in the general population due 75% higher basic reproduction numbers (1.75 x R_o) than in the general population setting [30,31]. In places with high-risk individuals (high-risk adults, elderly people and children aged 2-14 years), the required vaccination coverage can be higher than in the general population because vaccination effectiveness can be 20% lower (0.80 x effectiveness) than in healthy adults [31,32].

2.3. Vaccination coverage required to establish herd immunity against SARS-CoV-2 with infections among vaccinated individuals

The critical vaccination coverage required to establish herd immunity should be higher if infections occur among vaccinated individuals. All available vaccines are effective against severe illness, hospitalizations and deaths, but recent studies have found that fully vaccinated people who become infected with the Omicron variant can spread the virus to other individuals [11,28].

When infections occur among vaccinated individuals, the critical prevalence of protected individuals associated with herd immunity should be higher than without infections because infected vaccinated individuals should be considered as unprotected in herd immunity calculations. If r is the proportion of infections among vaccinated individuals, the prevalence of infected vaccinated individuals is equal to the vaccination coverage multiplied by the proportion of infections among them (V r).

The critical vaccination coverage (V_c) required to establish herd immunity was adjusted for infections among vaccinated individuals by taking into account that infected vaccinated individuals increased the prevalence of vaccine-induced protected individuals necessary to establish herd immunity by "V_c r":

$$I_c = I_c + (V_c\ r). \quad (5)$$

In this study, the following formula derived from Equations (4) and (5) was used to determine the critical vaccination coverage (V_c) that would be required to establish herd immunity adjusted for infections among vaccinated individuals:

$$V_c = I_c/(E - r). \quad (6)$$

Critical percentages of vaccination coverage required to establish herd immunity adjusted for infections among vaccinated individuals were determined for SARS-CoV-2 with R_o values ranging from 1.1 to 10 [20–24], levels of vaccination effectiveness ranging from 10% to 100%, and a proportion of infections among vaccinated individuals of 5% and 9.8% [11].

Before the spread of Omicron variant, reinfections were very infrequent among infected individuals, with reinfection rates of 0−1.1% [33]. Prior to Omicron, SARS-CoV-2 infections were associated with a Relative Risk of reinfection of 0.15 during 6 months compared with those without prior infection [34]. Nevertheless, Omicron variant is associated with a higher risk of reinfections than previous variants [11,28,35]. A study carried out in the United Kingdom, including 116,683 individuals identified with an Omicron infection, found a 9.8% proportion of SARS-CoV-2 reinfections [11]. Another study carried out in the United Kingdom using conditional Poisson regression to predict reinfection status (controlled for vaccine status, age, sex, ethnicity, asymptomatic status, region and specimen date), found that Omicron was associated with a 5.41 higher risk of reinfection compared with Delta [28]. The risk of reinfection with Omicron was 5.02 higher in vaccinated individuals and 6.38 higher in unvaccinated individuals compared with Delta [28]. A study carried out in South Africa found a 2.39 higher risk of reinfection for the Omicron variant [35]. Assuming that vaccine-induced protection is similar to natural protection after SARS-CoV-2 infection, it is possible to assume that a proportion of infections ranging from 5% or 9.5% could occur among vaccinated individuals.

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Infections among vaccination individuals can be explained by waning anti-SARS-CoV-2 vaccine-induced immunity over time. SARS-CoV-2 infections among vaccinated individuals under endemic conditions could likely occur between 6 months and 5 years after peak antibody response [36,37].

2.4. Assessment of herd immunity levels achieved with percentages of vaccination coverage of 70%, 80% and 90%

The WHO has proposed to achieve an overall Covid-19 vaccination coverage of 70% [9]. In this study, the model was used to assess whether the WHO Covid-19 vaccination coverage objective of 70% and alternative objectives of 80% and 90% could be sufficient to establish herd immunity against different SARS-CoV-2.

The vaccination coverage objective of 70% (or alternative objectives of 80% and 90%) was considered sufficient to establish herd immunity against SARS-CoV-2 when the vaccination coverage of 70% (or 80% and 90%) was equal or lower than the critical vaccination coverage ($V_{70} \le V_c$) that would be required for different levels of vaccination effectiveness. In this situation, the prevalence of vaccine-induced protected individuals achieved with Covid-19 vaccination is equal or higher than the critical prevalence of protected individuals blocking SARS-CoV-2 transmission ($I_v \ge I_c$).

Herd immunity levels associated with Covid-19 vaccination objectives of 70%, 80% and 90% were determined for populations without and with 9.8% reinfections among vaccinated individuals.

R_o values of SARS-CoV-2 that Covid-19 vaccination programs could block by achieving 70%, 80% and 90% vaccination coverage were determined using the formula:

$$R_o = 1/[1 - (V\ E)]. \quad (7)$$

R_o values of SARS-CoV-2 that Covid-19 vaccination programs could block by establishing herd immunity with 70%, 80% and 90% vaccination coverage depends on the prevalence of vaccine-induced protected individuals blocking SARS-CoV-2 transmission with these percentages of vaccination coverage. This prevalence was determined from the vaccination coverage (70%, 80% and 90%) and vaccination effectiveness in preventing SARS-CoV-2 infection (presented in Table 1) ($I_v = V \times E$). In this situation, the prevalence of vaccine-induced protected individuals is equal to the critical prevalence of protected individuals associated with herd immunity ($I_v = I_c$) against SARS-CoV-2. Covid-19 vaccination programs could not block transmission of viruses with R_o values associated with herd iummunity thresholds higher than the prevalence of vaccine-induced protected individuals generated with 70%, 80% and 90% vaccination coverage ($I_c > V \times E$).

2.5. Vaccination coverage required to establish herd immunity in populations with part of the population already protected against SARS-CoV-2

The vaccination coverage that would be required to establish herd immunity will be lower when part of the population is already protected against Covid-19 due to natural infections (I_n). In this situation, the prevalence of vaccine-induced protected individuals (I_v) that would be required to establish herd immunity is lower depending on the prevalence of individuals already protected ($I_v = I_c - I_n$). In this study, the vaccination coverage that would be required to establish herd immunity in communities when part of the population is already protected against Covid-19 due to natural infections was estimated using the following formula:

$$V_c = (I_c - I_n)/E. \quad (8)$$

In this formula, I_c is the prevalence of protected individuals required to establish herd immunity (herd immunity threshold), I_n is the prevalence individuals already protected against SARS-CoV-2 due to natural infections, and E is the level of Covid-19 vaccination effectiveness.

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Required percentages of vaccination coverage were determined for communities with a prevalence protected individuals of 10% and 20%, R_o values for SARS-CoV-2 ranging from 1.1 to 10, and levels of Covid-19 vaccination effectiveness ranging from 10% to 100%.

2.6. Statistical analysis

Microsoft Excel 2016 (v. 2203) was used to calculate percentages of vaccination coverage that would be required to establish herd immunity against SARS-CoV-2 for R_o values ranging from 1.1 to 10, vaccination effectiveness from 10% to 100%, and 0%, 5% or 9.8% infections among vaccinated individuals.

Microsoft Excel 2016 (v. 2203) was used to estimate levels of Covid-19 vaccination effectiveness required to establish herd immunity against SARS-CoV-2 (R_o values from 1.1 to 10) with vaccination programs achieving 70%, 80% and 90% coverage.

3. Results

3.1. Vaccination coverage required to establish herd immunity against SARS-CoV-2

Figure 1 and Supplement Table 2 present the vaccination coverage required to establish herd immunity against SARS-CoV-2 without infections among vaccinated individuals.

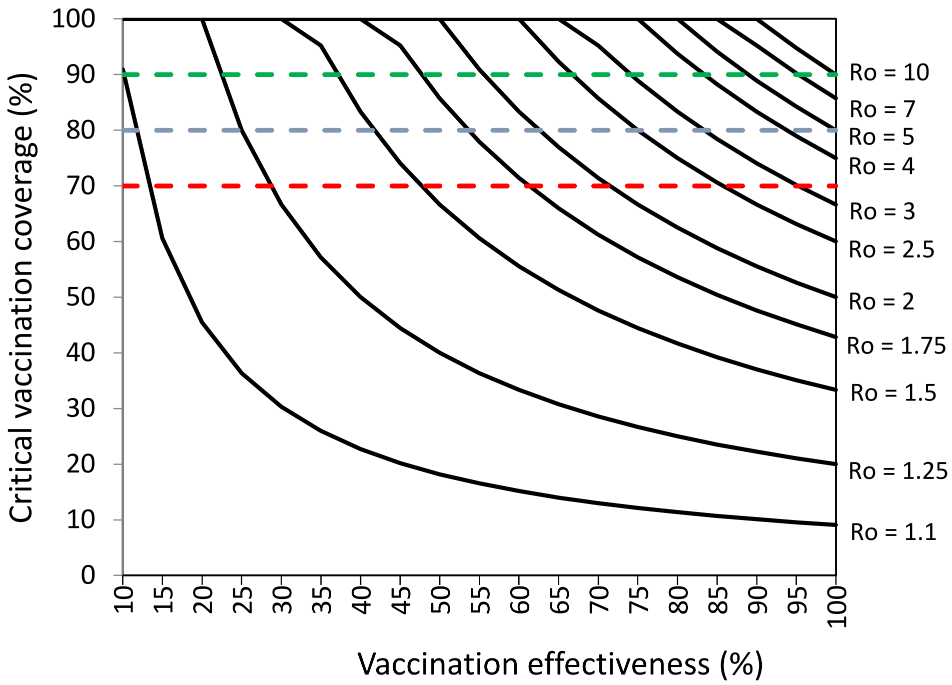

Figure 1. Vaccination coverage (%) required to establish herd immunity against SARS-CoV-2 with different reproductive numbers (Ro) by vaccination effectiveness (%). Objectives of vaccination coverage of 70%, 80% and 90% indicated dashed red, blue and green lines, respectively.

Figure 1 and Supplement Table 2 suggest that Covid-19 vaccination programs should achieve high percentages of vaccination coverage and high levels of Covid-19 vaccination effectiveness in order to establish herd immunity against SARS-CoV-2 with high levels of transmissibility (R_o values). Covid-19 vaccination programs achieving 70% vaccination effectiveness could establish herd immunity against viruses with R_o ranging from 1.1 to 3.25 with percentages of vaccination coverage from 13% to 98.9%, respectively. Vaccination programs achieving 80–100% vaccination effectiveness could establish herd immunity

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against viruses with R_o ranging from 1.1 to 10 with percentages of vaccination coverage from 9-10% to 90-100%, respectively.

3.2. Vaccination coverage required to establish herd immunity against SARS-CoV-2 with infections among vaccinated individuals

Figure 2 and Table 2 show that Covid-19 vaccination programs should achieve higher percentages of vaccination coverage and higher levels of effectiveness to establish herd immunity than those required without infections among vaccinated individuals. Covid-19 vaccination could establish herd immunity against SARS-CoV-2 with R_o values ranging from 1.1 to 10 with percentages of vaccination coverage of 10–100% and levels of vaccination effectiveness of 10–100%, when 9.8% infections occur among vaccinated individuals. Required percenatges of vaccination coverage would be 74–100% against virues with R_o values of 3–10, but vaccination efffectiveness should be 80–100%.

Table 2. Critical vaccination coverage (V_c) required to establish herd immunity against SARS-CoV-2 with reproductive numbers (R_o) from 1.1 to 10 by vaccination effectiveness (%), with 9.8% infections among vaccinated individuals.

Ro of SARS-CoV-2[b]	Critical vaccination coverage (%)[a] for Covid-19 vaccination effectiveness from 10% to 100%									
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1.1	–	89.1	45.0	30.1	22.6	18.1	15.1	13.0	11.3	10.1
1.25	–	–	99.0	66.2	49.8	39.8	33.2	28.5	24.9	22.2
1.5	–	–	–	–	82.9	66.4	55.4	47.5	41.6	37.0
1.75	–	–	–	–	–	85.4	71.2	61.1	53.4	47.5
2	–	–	–	–	–	99.6	83.1	71.2	62.3	55.4
2.25	–	–	–	–	–	–	92.3	79.1	69.3	61.6
2.5	–	–	–	–	–	–	–	85.5	74.8	66.5
2.75	–	–	–	–	–	–	–	90.7	79.3	70.6
3	–	–	–	–	–	–	–	95.0	83.1	73.9
3.25	–	–	–	–	–	–	–	98.6	86.3	76.8
3.5	–	–	–	–	–	–	–	–	89.1	79.2
3.75	–	–	–	–	–	–	–	–	91.4	81.3
4	–	–	–	–	–	–	–	–	93.5	83.1
4.25	–	–	–	–	–	–	–	–	95.3	84.8
4.5	–	–	–	–	–	–	–	–	97.0	86.2
4.75	–	–	–	–	–	–	–	–	98.4	87.5
5	–	–	–	–	–	–	–	–	99.8	88.7
6	–	–	–	–	–	–	–	–	–	92.4
7	–	–	–	–	–	–	–	–	–	93.8
8	–	–	–	–	–	–	–	–	–	98.5
9	–	–	–	–	–	–	–	–	–	97.0
10	–	–	–	–	–	–	–	–	–	99.8

a. $V_c = I_c$/Effectiveness. $I_c = 1 - (1/R_o)$. The critical vaccination coverage is not posible (−) when herd immunity could not be established with 100% vaccination coverage

b. The basic reproduction number R_o indicates the average number of secondary cases generated per infected case in a completely susceptible population

Critical percentages of vaccination coverage were 1–96% higher than those without infections among vaccinated individuals (presented in Figure 1). with higher vaccination coverage increases for lower levels of vaccination effectiveness. Required percentages of vaccination coverage were 1%–24% higher than those without infections among vaccinated individuals for levels of vaccination effectivenss ≥50% and 20%–96% higher than

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those without infections among vaccinated individuals for levels of vaccination effectiveness <50%.

Vaccination programs achieving 70% vaccination effectiveness could establish herd immunity against viruses with R_o ranging from 1.1 to 2.25 with percentages of vaccination coverage from 15.1% to 92,3%, respectively. Vaccination programs achieving 80% vaccination effectiveness could establish herd immunity against viruses with R_o ranging from 1.1 to 3 with percentages of vaccination coverage from 13% to 98.6%. Vaccination programs achieving 90% vaccination effectiveness could establish herd immunity against viruses with R_o ranging from 1.1 to 4.75 with percentages of vaccination coverage from 11.3% to 99.8%. Vaccination programs achieving 100% vaccination effectiveness could establish herd immunity against viruses with R_o ranging from 1.1 to 10 with percentages of vaccination coverage from 10.1% to 99.8%.

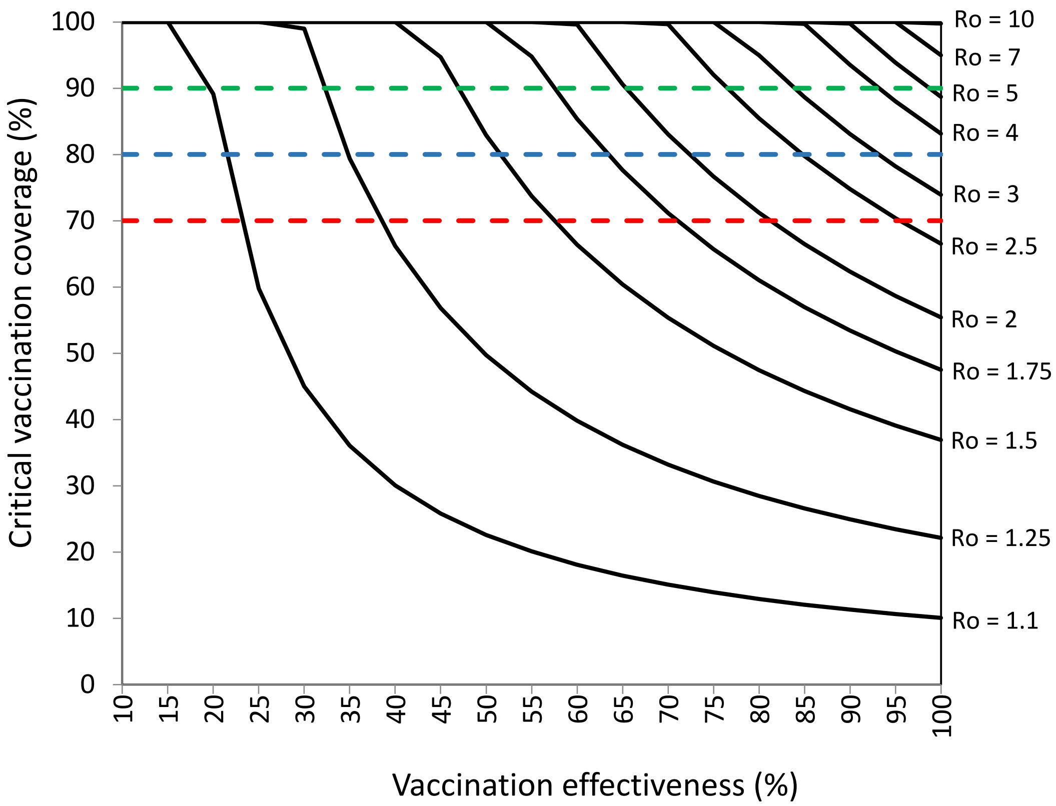

Figure 2. Vaccination coverage (%) required to establish herd immunity against SARS-CoV-2 with different reproductive numbers (Ro) by vaccination effectiveness (%) in a population with 9.8% infections among vaccinated individuals. Objectives of vaccination coverage of 70%, 80% and 90% indicated with dashed red, blue and green lines, respectively.

In close settings, very high percentages of vaccination coverage are required to block SARS-CoV-2 transmission due to their 75% higher transmissibility. For example, the vaccination coverage is 89.1% against viruses with R_o = 2 (R_o = 3.5 in the close setting) with 90% vaccination effectiveness (Figure 2, Table 2). In places with high-risk individuals, very high levels of vaccination coverage are required to block SARS-CoV-2 transmission due to their lower levels of vaccine effectiveness. For example, the vaccination coverage is 92.3% against viruses with R_o=2.25 and 90% vaccination effectiveness (72% in high-risk individuals) (Figure2, Table 2).

Table 3 and Figure 3 present the vaccination coverage that would be required to establish herd immunity against SARS-CoV-2 with 5% infections among vaccinated individuals for different levels of vaccination effectiveness.

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Table 3. Critical vaccination coverage (V_c) required to establish herd immunity against SARS-CoV-2 with reproductive numbers (R_o) from 1.1 to 10 by vaccination effectiveness (%), with 5% infections among vaccinated individuals.

R_o of SARS-CoV-2[b]	Critical vaccination coverage (%)[a] for Covid-19 vaccination effectiveness from 10% to 100%									
	10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
1.1	–	60.6	36.4	26.0	20.2	16.5	14.0	12.1	10.7	9.6
1.25	–	–	80.0	57.1	44.4	36.4	30.8	26.7	23.5	21.1
1.5	–	–	–	95	74.1	60.6	51.3	44.4	39.2	35.1
1.75	–	–	–	–	95	77.9	65.9	57.1	50.4	45.1
2	–	–	–	–	–	90.9	76.9	66.7	58.8	52.6
2.25	–	–	–	–	–	–	85.5	74.1	65.4	58.5
2.5	–	–	–	–	–	–	92	80.0	70.6	63.2
2.75	–	–	–	–	–	–	98	84.8	74.9	67.0
3	–	–	–	–	–	–	–	88.9	78.4	70.2
3.25	–	–	–	–	–	–	–	92.3	81.4	72.9
3.5	–	–	–	–	–	–	–	95	84.0	75.2
3.75	–	–	–	–	–	–	–	98	86.3	77.2
4	–	–	–	–	–	–	–	100	88.2	78.9
4.25	–	–	–	–	–	–	–	–	90.0	80.5
4.5	–	–	–	–	–	–	–	–	91.5	81.9
4.75	–	–	–	–	–	–	–	–	92.9	83.1
5	–	–	–	–	–	–	–	–	94.1	84.2
6	–	–	–	–	–	–	–	–	98	87.7
7	–	–	–	–	–	–	–	–	–	90.2
8	–	–	–	–	–	–	–	–	–	92.1
9	–	–	–	–	–	–	–	–	–	93.6
10	–	–	–	–	–	–	–	–	–	94.7

a. $V_c = I_c$/Effectiveness. $I_c = 1 - (1/R_o)$. The critical vaccination coverage is not possible (−) when herd immunity could not be established with 100% vaccination coverage

a. The basic reproduction number R_o indicates the average number of secondary cases generated per infected case in a completely susceptible population

Table 3 and Figure 3 show that critical percentages of vaccination coverage would be 1–11% higher than those without infections among vaccinated individuas (presented in Figure 1 and Supplement table 2) for levels of vaccination effectiveness ≥50% and 14–33% higher for levels of vaccination effectiveness <50%.

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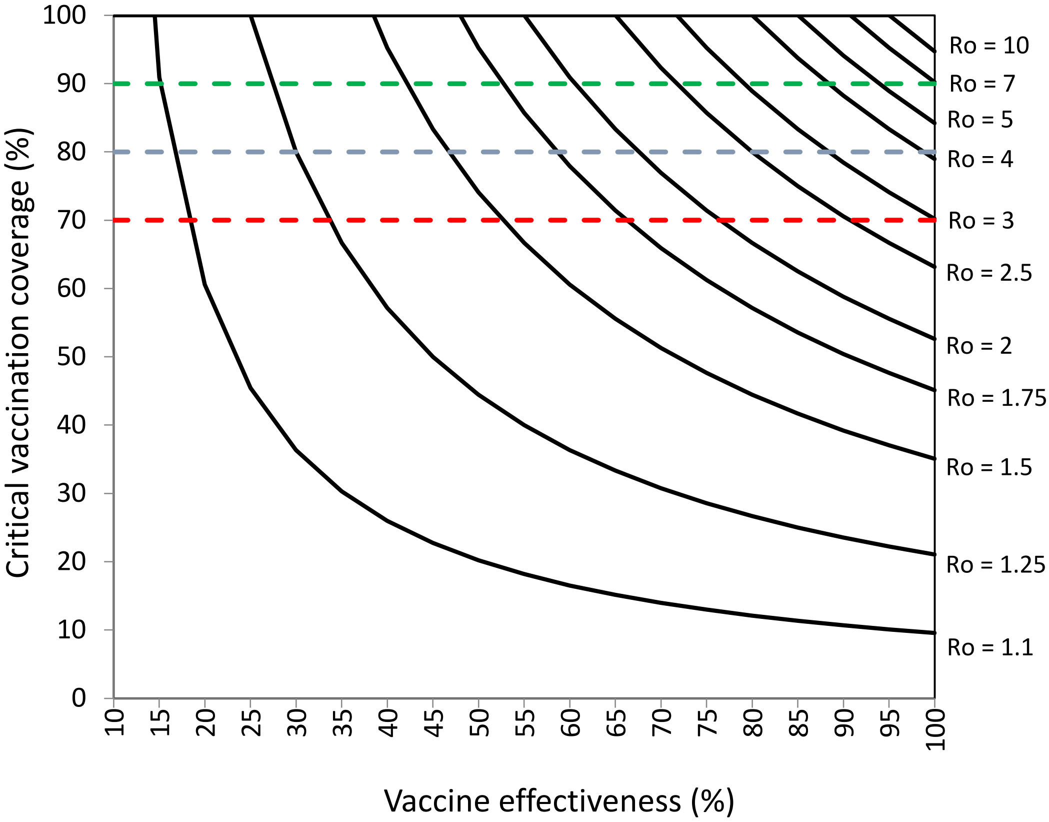

Figure 3. Vaccination coverage (%) required to establish herd immunity against SARS-CoV-2 with different reproductive numbers (Ro) by vaccination effectiveness (%) in a population with 5% infections among vaccinated individuals. Objectives of vaccination coverage of 70%, 80% and 90% indicated with dashed red, blue and green lines, respectively.

3.3. Assessment of herd immunity levels achieved with percentages of vaccination coverage of 70%, 80% and 90%

Table 4 presents levels of Covid-19 vaccination effectiveness necessary to establish herd against SARS-CoV-2 with R_o values from 1.1 to 10 when vaccination coverage is 70%, 80% and 90%, with 0% and 9.8% infections among vaccinated individuals. Results presented in this Table show that infections among vaccination individuals reduce herd immunity effects of Covid-19 vaccination programs due to two negative effects: 1) Vaccination programs could establish herd immunity against SARS-CoV-2 with R_o values lower than those without infections among vaccinated individuals. 2) Vaccination effectiveness levels necessary to establish herd immunity against SARS-CoV-2 are higher than those without infections among vaccinated individuals.

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Table 4. Vaccination effectiveness necessary to establish herd immunity against SARS-CoV-2 with basic reproduction number ranging from 1.1 to 10 in populations with percentages of vaccination coverage of 70%, 80% and 90%, with 0% and 9.8% infections among vaccinated individuals.

	Covid-19 vaccination effectiveness (%) required to establish herd immunity with 70%, 80% and 90% vaccination coverage					
	Vaccination coverage[a]			**Vaccination coverage and 9.8% infections in vaccinated individuals[b]**		
R_o of SARS-CoV-2	**70%**	**80%**	**90%**	**70%**	**80%**	**90%**
1.1	13.0	11.4	10.1	22.8	21.2	19.9
1.25	28.6	25.0	22.2	38.4	34.8	32.0
1.5	47.6	41.7	37.0	57.4	51.5	46.8
1.75	61.2	53.6	47.6	71.0	63.4	57.4
2	71.4	62.5	55.6	81.2	72.3	65.4
2.25	79.4	69.4	61.7	89.2	79.2	71.5
2.5	85.7	75.0	66.7	95.5	84.8	76.5
2.75	90.9	79.5	70.7	–	89.3	80.5
3	95.2	83.3	74.1	–	93.1	83.9
3.25	98.9	86.5	76.9	–	96.3	86.7
3.5	–	89.3	79.4	–	99.1	89.2
3.75	–	91.7	81.5	–	–	91.3
4	–	93.8	83.3	–	–	93.1
4.25	–	95.6	85.0	–	–	94.8
4.5	–	97.2	86.4	–	–	96.2
4.75	–	98.7	87.7	–	–	97.5
5	–	100.0	88.9	–	–	98.7
6	–	–	92.6	–	–	–
7	–	–	95.2	–	–	–
8	–	–	97,2	–	–	–
9	–	–	98,8	–	–	–
10	–	–	100.0	–	–	–

a. Effectiveness = I_c/Vaccination coverage. The effectiveness is not indicated (−) when herd immunity could not be established with 100% vaccination coverage.

b. Effectiveness = (I_c/Vaccination coverage) + infection rate among vaccinated individuals. The effectiveness is not indicated (−) when herd immunity could not be established with 100% vaccination coverage

Results presented on Table 4, as well as those presented in Figure 2 and Table 2, suggest that the vaccination coverage objective of 70%, proposed by the WHO, could be sufficient to establish herd immunity against SARS-CoV-2 with R_o values from 1.1 to 2.5 when 9.8% infections among vaccinated individuals. Alternative vaccination coverage objectives of 80% and 90% could be sufficient against viruses with R_o values from 1.1 to 3.5 and from 1.1 to 5, respectively.

Without infections among vaccinated individuals, vaccination coverage objectives of 70%, 80% and 90% could be sufficient against viruses with R_o values from 1.1 to 3.25, 1.1 to 5 and 1.1 to 10, respectively (Figure 1, Table S2). With 5% infections among vaccinated individuals, vaccination coverage objectives of 70%, 80% and 90% could be sufficient against viruses with R_o values from 1.1 to 2.75, 1.1 to 4 and 1.1 to 6, respectively (Figure 3 Table 3).

Table 5 presents R_o values of SARS-CoV-2 that current Covid-19 vaccines could block by establishing herd immunity with 70%, 80% and 90% vaccination coverage, with 9.8% infections among vaccinated individuals. Available Covid-19 vaccines could establish herd immunity against the Omicron variant with R_o values ranging from 1.09 to 1.51 and against the Delta variant with with R_o values ranging from 1.56 to 3.71, with higher R_o values for vaccination programs achieving 90% vaccination coverage.

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Table 5. R_o of SARS-CoV-2 that Covid-19 vaccination programs could block by achieving 70%, 80% and 90% vaccination coverage, when 9.8% infections occur among vaccinated individuals.

Vaccine	R_o of SARS-CoV-2 blocked by Covid-19 vaccination programs achieving 70%, 80% and 90% vaccination coverage[a]								
	Vaccination coverage			Vaccination coverage			Vaccination coverage		
	70%	80%	90%	70%	80%	90%	70%	80%	90%
	Ancestral variant			Delta variant			Omicron variant		
	R_o	R_o	R_o	R_o	R_o	R_o	R_o	R_o	R_o
Moderna	2.36	2.92	3.84	2.32	2.85	3.71	1.37	1.44	1.52
Pfizer/BioNTech	2.14	2.56	3.18	2.08	2.46	3.01	1.31	1.38	1.44
Sputnik	2.14	2.56	3.18	2.11	2.51	3.09	1.31	1.38	1.44
Novavax	2.05	2.41	2.93	2.02	2.37	2.86	1.30	1.36	1.43
Covaxin	1.79	2.02	2.32	1.77	1.99	2.27	1.25	1.29	1.34
Oxford/Astra-Zeneca	1.59	1.74	1.92	1.71	1.90	2.14	1.22	1.27	1.31
Sinopharm	1.69	1.87	2.10	1.67	1.84	2.06	1.21	1.25	1.29
Janssen	1.77	1.99	2.27	1.61	1.77	1.95	1.19	1.23	1.26
CoronaVac	1.35	1.42	1.50	1.34	1.41	1.48	1.11	1.13	1.15
Convidecia	1.58	1.72	1.89	1.56	1.69	1.85	1.09	1.11	1.12
AstraZeneca (AZ 3D)				2.43	3.05	4.10	1.79	2.02	2.32
Pfizer (PF 3D)				2.47	3.13	4.26	1.89	2.16	2.53

a. R_o values obtained for levels of effectiveness in preventing SARS-CoV-2 infection for all vaccines (Table 1) and effectiveness in preventing symptomatic infection for AZ 3D and PF 3D vaccination [28]

In individuals vaccinated with 3 doses of Pfizer vaccine (PF 3D vaccination status) and in those vaccinated with two doses of AstraZeneca vaccine plus a booster dose of RNA vaccine (AZ 3P vaccination status), 77% and 73% effectiveness in preventing symptomatic Omicron infection and 93.8% and 94.3% effectiveness in preventing symptomatic Delta respectively, respectively, have been obtained [28]. Consequently, these vaccination strategies could block transmission of SARS-CoV-2 with higher R_o value than those obtained taken into account levels of effectiveness in preventing Omicron and Delta infection (Table 5).

When infections dfo not occur among vaccinated individuals, Covid-19 vaccination programs could establish herd immunity againts SARS-CoV-2 with R_o values 7–13% higher than those obtained with 9.8% infections among vaccinated individuals (Table 6).

Table 6. R_o of SARS-CoV-2 that Covid-19 vaccination programs could block by achieving 70%, 80% and 90% vaccination coverage establish herd immunity, without infections among vaccinated individuals.

Vaccine	R_o of SARS-CoV-2 blocked by Covid-19 vaccination programs achieving 70%, 80% and 90% vaccination coverage[a]								
	Vaccination coverage			Vaccination coverage			Vaccination coverage		
	70%	80%	90%	70%	80%	90%	70%	80%	90%
	Ancestral variant			Delta variant			Omicron variant		
	R_o	R_o	R_o	R_o	R_o	R_o	R_o	R_o	R_o
Moderna	2.81	3.79	5.81	2.75	3.68	5.52	1.51	1.62	1.76
Pfizer/BioNTech	2.51	3.21	4.42	2.43	3.05	4.10	1.45	1.54	1.66
Sputnik	2.51	3.21	4.42	2.47	3.13	4.26	1.45	1.54	1.66
Novavax	2.39	2.98	3.95	2.35	2.91	3.82	1.43	1.52	1.63
Covaxin	2.04	2.40	2.92	2.02	2.36	2.84	1.36	1.44	1.52
Oxford/Astra-Zeneca	1.79	2.02	2.31	1.93	2.23	2.64	1.34	1.40	1.48
Sinopharm	1.91	2.19	2.58	1.88	2.16	2.52	1.32	1.39	1.46
Janssen	2.02	2.36	2.84	1.81	2.05	2.36	1.30	1.36	1.42
CoronaVac	1.49	1.60	1.73	1.47	1.58	1.71	1.20	1.24	1.28
Convidecia	1.77	1.98	2.26	1.75	1.95	2.22	1.18	1.21	1.25
AstraZeneca (AZ 3D)				2.91	4.01	6.42	2.04	2.40	2.92
Pfizer (PF 3D)				2.97	4.14	6.81	2.17	2.60	3.26

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a. R_o values obtained for levels of effectiveness in preventing SARS-CoV-2 infection for all vaccines (Table 1) and effectiveness in preventing symptomatic infection for AZ 3D and PF 3D vaccination [28]

The results presented in Table 4, Table 5 and Table 6 suggest that Covid-19 vaccination programs should achieve higher levels of effectiveness in preventing Omicron infection in order to prevent prevent transmission of SARS-CoV-2 with high transmissibility.

As on 10 April 2022, the vaccination coverage with complete doses ranged from 0.1% oin Burundi to 96.3% in United Arab Emirates (Supplement Table 1) [4]. The coverage for completed vaccination was <70% in 73% of the countries of the world, and it was ≥90% in 3.2% of the countries of the world.

3.4. Vaccination coverage required to establish herd immunity against SARS-CoV-2 when part of the population is already protected

Figure 4 and Supplement Table 3 present percentages of vaccination coverage required to establish herd immunity against SARS-CoV-2 for levels of Covid-19 vaccination effectiveness from 10% to 100% when the prevalence of protected individuals of 10% and 9.8% infections occur asmong vaccinated individuals.

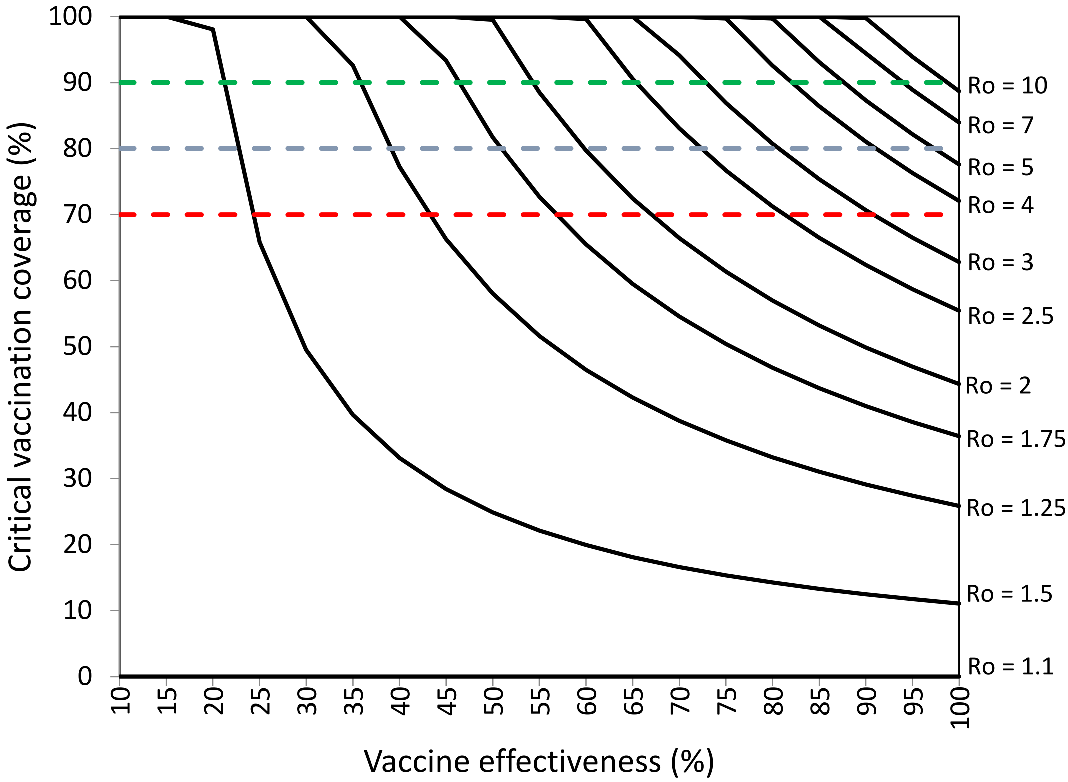

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Figure 4. Vaccination coverage (%) required to establish herd immunity against SARS-CoV-2 with different basic reproductive numbers (Ro) by vaccination effectiveness (%) in a population with 10% prevalence of protected individuals and 9.8% infections among vaccinated individuals. Objectives of vaccination coverage of 70%, 80% and 90% indicated with dashed red, blue and green lines, respectively.

Figure 4 shows that critical percentages of vaccination coverage are quite similar with those without 9.8% infections among vaccinated individuals (Figure 1) when 10% of the population is already protected against SARS-CoV-2 and 9.8% infections occur among vaccinated individuals. The critical vaccination coverage was 14% for viruses with R_o=1.25 and vaccine effectiveness of 80%, 80% for viruses with R_o=2 and vaccine effectiveness of 60%, and 90% for viruses with R_o=3.75 and vaccine effectiveness of 80%.

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Figure 5 and Supplement Table 4 present percentages of vaccination coverage required to establish herd immunity against SARS-CoV-2 for levels of Covid-19 vaccination effectiveness from 10% to 100% in a population with a prevalence of protected individuals of 20% and 9.8% infections among vaccinated individuals.

In a community with a prevalence of protected individuals of 20% (Figure 5), the vaccination coverage required is 45% for viruses with R_o=1.75 and vaccine effectiveness of 80%, 60% for viruses with R_o=2 and vaccine effectiveness of 60%, and 76% for viruses with R_o=3.75 and vaccine effectiveness of 80%. In a community with a prevalence of protected individuals of 25% (Figure 6), the vaccination coverage required 25% for viruses with R_o=1.75 and vaccine effectiveness of 80%, 50% for SARS-CoV-2 with R_o=2 and vaccine effectiveness of 60%, and 96% for viruses with R_o=3.75 and vaccine effectiveness of 60%.

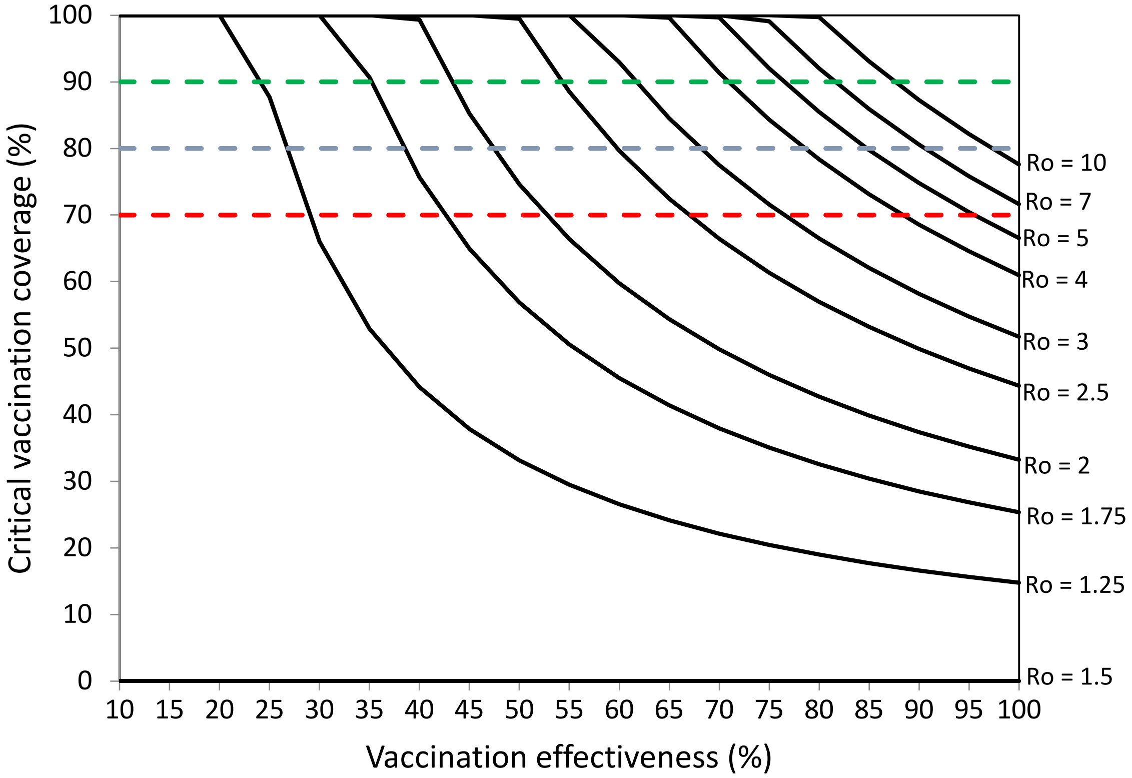

Figure 5. Vaccination coverage (%) required to establish herd immunity against SARS-CoV-2 with different basic reproductive numbers (Ro) by vaccination effectiveness (%) in a population with 20% prevalence of protected individuals and 9.8% infections among vaccinated individuals. Objectives of vaccination coverage of 70%, 80% and 90% indicated with dashed red, blue and green lines, respectively.

Figure 4 and Figure 5 suggest that vaccination would not be necessary to establish herd immunity against viruses with R_o=1.1 and R_o=1.25 when the prevalence of protected individuals is ≥10% and ≥20%, respectively, because the critical prevalence of protected individuals necessary to establish herd immunity is already achieved without vaccination. By contrast, percentages of vaccination coverage > 70% are necessary to establish herd immunity against viruses with Ro ≥ 2 when 10% of the population already protected and vaccination effectiveness is lower than 70%; against viruses with Ro ≥ 2.25 when 20% of the population already protected and vaccination effectiveness is lower than 70%, and against viruses with Ro ≥ 2.75 when 25% of the population already protected and vaccination effectiveness is lower than 70%.

4. Discussion

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The study assessed percentages of Covid-19 vaccination coverage that would be required to establish herd immunity in the population against SARS-CoV-2 for estimated levels of Covid-19 vaccination effectiveness. When Covid-19 vaccines were available on 2021, it was expected that achieving 70% vaccination coverage could be sufficient to establish anti-SARS-CoV-2 herd immunity in the population [9,10]. Nevertheless, the results obtained in this study suggest that high percentages of vaccination coverage and high levels of vaccination effectiveness are necessary to block transmission of SARS-CoV-2 with greater infectious capacity.

The study suggests that achieving 70% vaccination coverage could be sufficient to prevent transmission of SARs-CoV-2 with low and moderate transmissibility (R_o values from 1.1 to 3.25), but not against SARS-CoV-2 with high and very high transmissibility (R_o values higher 3.25). On the other hand, vaccination effectiveness should be higher than 90.9% to block transmission of viruses with R_o values from 2.75 to 3.25 with a 70% vaccination coverage.

Vaccination programs achieving 80% vaccination coverage could be sufficient to prevent transmission of SARs-CoV-2 with high transmissibility (R_o values from 3.25 to 5), but vaccination effectiveness should be higher than 86.5%. Vaccination programs achieving 90% vaccination coverage could be sufficient to prevent transmission of viruses with very high transmissibility (R_o values >5), but vaccination effectiveness should be higher than 88.9%.

The study suggest that higher levels of vaccination coverage would be required to establish herd immunity against SARS-CoV-2 in close settings and places with high-risk individuals due to their higher transmission levels and lower levels of Covid-19 vaccination effectiveness, respectively. Higher levels of vaccination coverage would be required also in clusters of individuals with a higher SARS-CoV-2 transmission (R_o) than in the general population setting. Similar results have been obtained for influenza vaccination [38].

This study found that infections among vaccinated individuals reduce herd immunity effects of Covid-19 vaccination programs due to three negative effects: 1) Covid-19 vaccination programs should achieve higher percentages of vaccination coverage to establish herd immunity in the population than those without infections among vaccinated individuals. 2) Vaccination programs could establish herd immunity against SARS-CoV-2 with Ro values lower than those without infections among vaccinated individuals. 3) Vaccination effectiveness levels necessary to establish herd immunity against SARS-CoV-2 are higher than those required without infections among vaccinated individuals.

This study found that Covid-19 vaccines should achieve higher levels of effectivensss in preventing Omicron infection to block transmission of SARS-CoV-2 in the community. Available Covid-19 vaccines are effective in preventing severe disease and mortality from different SARS-CoV-2 variants, but they are less effective in preventing Omicron infections [7,8,27–28]. The effectiveness in preventing severe Omicron infections was 71–73% using Astra/Zeneca, Moderna and Pfizer/BioNTech vaccines and 37–67% using other vaccines; the effectiveness in preventing severe Delta infections was 94–97% using Astra/Zeneca, Moderna and Pfizer/BioNTech vaccines and 49–89% using other vaccines; and the effectiveness in preventing Delta infections was 94–97% using Astra/Zeneca, Moderna and Pfizer/BioNTech vaccines and 49–89% using other vaccines [8] (Table 1). By contrast, the effectiveness in preventing Omicron infections was 43–48% using Moderna, Pfizer/BioNTech, Sputnik and Novavax vaccines and 24–38% using other vaccines [8] (Table 1). A study carried out in the United Kingdom assessing the impact of Omicron on vaccination effectiveness in preventing symptomatic infection found levels of vaccination effectiveness against Omicron infections ranging from 0% to 20% using two doses of vaccine and from 55% to 80% using three doses of vaccine [28]. A network meta-analysis assessing the relative efficacy of seven vaccines (Pfizer/BioNTech, Moderna, AstraZeneca, Janssen, Gamaleya, Sinopharm, Sinovac) in preventing symptomatic and severe Covid-19 found

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that the probability of being better than other competing vaccines in terms of efficacy in preventing severe Covid-19 was not statistically significant [29].

Infections among vaccinated individuals could be explained by waning vaccine-induced immunity and emergence of SARS-CoV-2 variants escaping immune response, resulting in lower levels of Covid-19 vaccination effectiveness [33–37]. The information on reinfection rates and infection rates among vaccinated individuals is important for public health decision making. First, higher percentages of vaccination coverage should be achieved to block SARS-CoV-2 transmission when infections occur among vaccinated individuals. Second, mask-wearing and other preventive behaviors could be used to reduce SARS-CoV-2 transmission from infected vaccinated individuals.

Required percentages of vaccination coverage would be lower when 10-20% of the population was already protected against SARS-CoV-2 due to natural infections. Similar results have been obtained for influenza vaccination [38]. In this situation, however, Covid-19 vaccination should be recommended to all individuals for several reasons. First, Covid-19 vaccination prevent individual infections, especially in high-risk individuals. Second, it is necessary to develop seroprevalence studies in representative samples of the population in order to estimate the real prevalence of protected individuals in the population. Third, a complex and costly screening and vaccination program should be developed where all individuals of the population should be screened for SARS-CoV-2 antibodies and vaccines should be given only unprotected individuals.

The WHO has proposed to achieve 40% in all countries by end-2021 and 70% by mid-2022 [9,39]. Based on the results obtained in the study, the vaccination coverage objective of 70% could be adequate against SARS-CoV-2 with R_o values of 1.1–2.5, while percentages of vaccination coverage of 80% and 90% could be more adequate against viruses with R_o values of 2.5–3.5 and >3.5, respectively. Percentages of vaccination coverage of 80% and 90% are more adequate than 70% because herd immunity levels achieved with 70% vaccination coverage can be reduced significantly by factors reducing Covid-19 vaccination effectiveness (emergent variants, infections, high risk individuals) and by factors increasing SARS-CoV-2 transmissibility (close settings).

The study has several limitations. First, percentages of vaccination coverage that would be required to establish herd immunity against SARS-CoV-2 were determined taking into account SARS-CoV-2 trasmissibility and Covid-19 vaccination effectiveness. This method is based on the following assumptions: (1) homogeneous mixing of individuals within the population and (2) homogeneous distribution of protected individuals within the population [17–21]. If the distribution of protected individuals is not homogeneous, required percentages of vaccination coverage would be higher or lower in places with lower or higher levels of protected individuals, respectively. Nevertheless, it is possible to assume a homogeneous mixing of persons and homogeneous distribution of protected individuals within vaccinated population groups [20,21]. Second, percentages of vaccination coverage that would be required to establish herd immunity were determined for SARS-CoV-2 with values of R_o from 1.1 to 10. Required percentages of vaccination coverage could be lower using measures for preventing SARS-CoV-2 transmission, such as mask-wearing and physical distancing. For this reason, results obtained in this study can be considered conservative, as community-wide mask wearing and physical distancing could contribute to reduce required percentages of vaccination coverage. Nevertheless, levels of Covid-19 vaccination effectiveness are higher and more consistent than those that could be achieved with mask-wearing and social distancing [9,39]. In addition, it is difficult to know the additional effectiveness that could be achieved in the community with mask-wearing because different types of masks could be used and they are not used in all places and during all time [40]. Third, percentages of vaccination coverage that would be required to establish herd immunity were determined for SARS-CoV-2 with Ro values from 1.1 to 10. Higher critical percentages of vaccination would be required against new SARS-CoV-2 variants with R_o values higher than 10. Nevertheless, the range of R_o values assumed in this study has been found in studies assessing R_o values of SARS-CoV-2 [20–24], and transmissibility of future

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variants should be in the range of values assumed in the study. Forth, the study determined percentages of vaccination coverage that would be required to establish herd immunity with 0%, 5% and 9.8% infection rates among vaccinated individuals. Higher critical percentages of vaccination would be required against SARS-CoV-2 variants with infections rates higher than 9.8%. Neverthelesss, it is possible to assume infection rates of 0–9.8% for new SARS-CoV-2 variants because a infection rate of 9.8% has been observed for Omicron [9], and future vaccines could be associated with a higher efficacy and effectiveness in preventing infections among vaccinated individuals.

Covid-19 vaccination is the key preventive measures included in the Covid-19 Strategic Preparedness and Response Plan (SPRP) of the WHO [41]. The objectives of the SPRP are to suppress transmission, reduce exposure, prevent infection and reduce morbidity and mortality from Covid-19 [41]. Covid-19 vaccination must be deployed in combination with other preventive measures and diagn1ostic and therapeutic activities to constitute a strong and effective response to Covid-19 pandemic.

Vaccination strategies to block SARS-CoV-2 transmission in the population by means of achieving critical percentages of vaccination coverage can be implemented using stratified vaccination, where different states or populations groups are vaccinated in several phases. The strategy proposed by the WHO to achieve high percentages of vaccination coverage (at least 70% by mid-2022) considers three steeps: Phase 1) vaccination of older adults and high-risk groups of all ages. Phase 2) extensive vaccination of the full adult age group. Phase 3) extensive vaccination of adolescents [39]. The objective of the first vaccination steep is to reduce and mortality from Covid-19, while the objectives in the second and third vaccination steeps are also to reduce SARS-CoV-2 transmission [39]. Different population and age groups have been included in stratified vaccination programs developed by countries of the world. From a practical point of view, herd immunity can be considered established in each population group (strate) when vaccination coverage is equal to or higher than the critical coverage ($V \geq V_c$) and when vaccine-induced immunity protection with be higher than the herd immunity threshold ($I_V \geq I_c$) [42]. Nevertheless, global vaccine-induced immunity protection will be higher than the herd immunity threshold when vaccination coverage is equal to or higher than the critical coverage all population groups.

Each country should use vaccination as a tool to reach a "new normal", where social and economic activity are resumed to the greatest extent possible while minimizing negative impacts [43]. The WHO proposes four levels of Covid-19 vaccination coverage: low, medium, high and very high [43]. Low and medium levels of vaccination coverage must be complemented with intensive prevention measures because movements along the socioeconomic dimension increase SARS-CoV-2 transmission (basic reproductive numbers). High and very high levels of vaccination coverage must be achieved in countries moving to a more normal setting of social and economic activity because in this situation prevention measures are reduced. The results obtained in the study suggest that, in countries moving to a more normal setting of social and economic activity, the vaccination objective should be at least the vaccination coverage that would be required to block SARS-CoV-2 transmission in the community, based on transmissibility of SARS-CoV-2 (R_o values) and vaccination effectiveness.

As on 10 April 2022, the vaccination coverage for completed vaccination was 58.2% in the World, 73.2% in South America, 67.7% in Asia, 65.3% in Europe, 62.9% in Oceania, 62.7% in North America and 15.4% in Africa [4]. In addition, the vaccination coverage for completed vaccination was <70% in 73% of the countries of the world. Based on the results obtained in this study, percentages of Covid-19 vaccination coverage should be increased in most countries of the world in order to increase individual and herd immunity protection. Several strategies could be developed to increase percentages of Covid-19 vaccination coverage, including advanced nominal vaccination programs, health education activities, strategies to increase vaccination access [44,45], strategies to reduce vaccination hesitance [46,47], administrative measures [48], and strategies to increase vaccination acceptance and confidence [49–51].

5. Conclusions

High percentages of vaccination coverage and high levels of vaccination effectiveness are necessary to block transmission of SARS-CoV-2 with greater infectious capacity. Covid-19 vaccination programs with 70% vaccination effectiveness could establish herd immunity against SARS-CoV-2 with values of R_0 from 1.1 to 3.25 and vaccination programs with >80% vaccination effectiveness against viruses with values of R_0 from 1.1 to 10. The vaccination coverage objective of 70% could be adequate against SARS-CoV-2 with R_0 values of 1.1–2.5, while percentages of vaccination coverage of 80% and 90% could be more adequate against viruses with Ro values of 2.5–3.5 and >3.5, respectively.

The study found that Covid-19 vaccines should achieve higher levels of effectiveness in preventing Omicron infection to block SARS-CoV-2 transmission in the community. Percentages of Covid-19 vaccination coverage should be increased in most countries of the world in order to increase individual and herd immunity protection.

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